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USAARL REPORT NO. 71-24

THE TESTING OF THERMAL PROTECTIVE CLOTHING IN A REPRODUCIBLE FUEL FIRE ENVIRONMENT, A FEASIBILITY STUDY

BY

John D. Albright
Francis S. Knox, III
David R. DuBois
George M. Keiser

June 1971

U. S. ARMY AEROMEDICAL RESEARCH LABORATORY

Fort Rucker, Alabama

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U. S. Army Medical Research and Development Command

FOREWORD

Research discussed in this report was accomplished by the Bioengineering and Evaluation Division as a part of Air Force Contract # FX2826-70-05327 between May 1970 and March 1971. A portion of the effort was performed by Enertech Corporation under Army Contract # DABC01-71-C-0090.

ABSTRACT

This report sets forth the conceptual design for a facility intended for development and evaluation of thermal protective clothing in a reproducible fuel fire environment. The methods developed relate thermal characteristics of fabrics to biomedical aspects of burn prevention. A number of bioengineering problems are identified, the resolution of which is expensive and time consuming. It is concluded that construction of the facility designed is technically feasible. Due to the magnitude and complexity of the bioengineering problems identified, and because of advances in laboratory testing methods, however, construction of such a facility is not considered to be a prudent expenditure of public funds at this time. Operationally oriented bioengineering/aeromedical evaluation of thermal protective clothing systems remains essential.

APPROVED: Robert W. Bailey
ROBERT W. BAILEY
COLONEL, MS
Commanding

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THE TESTING OF THERMAL PROTECTIVE CLOTHING IN A REPRODUCIBLE FUEL FIRE ENVIRONMENT, A FEASIBILITY STUDY

INTRODUCTION:

In spite of technological advances and increased concern by aircraft designers, fire associated with aircraft accidents continues to be a major cause of mortality and morbidity in military aircraft operations. During the past few years numerous fabrics designed to provide protection against fire have been developed. Methods for testing these fabrics have ranged from rather simple laboratory tests to exposure to open pit fuel fires. Investigators concerned with thermal protection have rarely agreed upon the interpretation of the results of such testing when attempting to relate these results to the subject of interest, human skin. Because of the interest and concern for aviation personnel held by this laboratory it was decided to initiate an integrated medical/physiological/engineering approach to this problem might provide a simple, dynamic, reproducible method of quantifying the important parameters of thermal protective clothing. With the support of the USAF Life Support Program Office, Air Force Systems Command, such an effort was begun in May 1970. A portion of the study was performed by Enertech Corporation of New York.

This is a report of the first phase of the study. During this phase it was our purpose to determine the feasibility and basic design of a facility intended to reproduce the characteristics of a JP-4 fire in a consistent manner and to predict the effects of such a fire upon a man escaping from it. Furthermore, it was our purpose to devise a method of measuring the protection against burns offered by various ensembles of fire protective clothing.

The first portion of this report will review some of the commonly used methods of evaluating thermal protective clothing both at the laboratory bench and in the field laboratory. The second portion of the report deals with the feasibility of reproducing JP-4 fuel fires under controlled conditions. The third portion of the report presents our concept of the necessary instrumentation required for a facility such as the one considered in part two. Part four discusses some critical factors involved in the future management of this project. Finally, the fifth portion presents our conclusions and recommendations for future development.

PRESENT TEST METHODS OF MEASURING THERMAL CHARACTERISTICS OF FABRICS

Several test methods have been used by different agencies to evaluate the degree of protection that a test garment will provide in a post-crash environment. No single test provides more than a portion of the total picture. Laboratory methods in general give precise data regarding flammability and heat transfer characteristics of fabrics. The heat sources utilized in these laboratory methods may fail to simulate the combined radiative, convective, and conductive components of a post-crash fire because the respective proportions of these components are not adequately known. While most garments will perform in an open pit fire as would be predicted from laboratory data, occasionally there are some surprises; although in retrospect the explanation for the surprises is usually readily available.

For all their accuracy and reliability laboratory tests are not readily accepted by the layman manager who must decide to purchase a recommended item. When presented with laboratory data the layman will invariably ask, "But will it work in a real fire?" Thus, there has been a general acceptance of the open pit method of testing as the final hurdle in the technical evaluation of thermal protective clothing. Unfortunately, the open pit method has, to date, provided the least reproducible data of all the methods.

This section will be a brief review of the current laboratory and field tests which address the problem of a garment's ability to provide burn protection.

In the design and evaluation of thermal protective clothing, the following parameters are of primary interest: (1) the character of the thermal source; (2) the physical properties of the fabrics (density, strength, melt temperature, flammability, dyability, etc.); (3) the insulating and optical properties; (4) the aesthetic properties - feel of the fabric, moisture regain, comfort.

The thermal source of concern here is a JP-4 post-crash fire or an adequate simulation of one. This aspect is the subject of the report by Enertech, Inc. and is covered in Section II. The aesthetic properties are not of concern in this report except to note that in most cases there are trade-offs resulting in decreased thermal protection in favor of comfort. Finally, the physical characteristics and insulating properties of fabrics and garments are determined using a number of laboratory and field methods.

Flammability of fabrics can be adequately tested in the laboratory by subjecting the fabric to an ignition source (hot wire, flame or radiation) and noting flaming (if present) and flame propogation. Flammability and propogation tests are useful, especially if care is taken to use logical ignition sources. In the case of JP-4 fires an open flame seems to be the most logical choice.

Off-gasing tests are useful only insofar as they serve to elimiate candidates which emit either toxic or flammable gases.

Heat shrinkage tests define the fabric's shrinkage behavior under thermal loads and indicate the possibility of fabric rupture and contact burns. There are cases in properly engineered garments, however, when the increase in trapped air by heat puckered layers would result in increased thermal protection.

Thermogravometric and differential thermal analysis provide data about the physical-chemical nature of the fiber but do not contribute much understanding to the behavior of a fabric in a fire.

Flame impingement tests in which heat transfer through one or several layers of fabric is measured with thermocouples or calorimeters are useful in predicting the amount of burn protection a given material will afford. This is especially true if the method has been calibrated against living tissue.

Conductive heat tests in which the test specimen is heated with a hot plate under controlled pressure and heat transfer is measured with a calorimeter; it may give some indication of what happens when a heated fabric is tightly pressed against a part of the body. Such variables as pressure, moisture content of clothing, temperature and charring effects, however, make the reliability of this method questionable.

Tests using radiant heat sources are useful models only in that JP-4 fires are largely radiation sources. The energy levels in JP-4 fires are such that the convective component is still a severe threat for living tissue. Radiant heat sources are useful because they are controllable, although extreme care must be taken to match the spectrum of radiation from the fire to minimize errors due to the fabric's reflectance.

One recent addition to the laboratory methodology(1) combines independently controllable radiant and convective sources in a chamber suitable for testing 12 x 12 inch samples. Heat transfer as well as flammability and shrinkage can be studied. The disadvantage of this test, as with all "lab" tests, is that they do not test the entire ensemble through a fire.

To date, the only simulation capable of addressing the aerodynamic factors has been the open pit test. Table I lists a number of such pits which already exist. The Navy (NADC, Johnsville, Pennsylvania) and the Army (Natick Labs, Sudbury Annex) both have constructed fire pits. Both facilities exhibit a common approach to simulating post-crash fires. This approach involves dragging a manikin wearing the test garment through the flames of an open pit fire. In both cases, the fuel is spilled on a pool of water and ignited with a torch. In order to cope with the variability in the fires introduced by the effect of wind, various kinds of partial walls have been erected at both fire pits. The walls at the Natick fire pit do not adequately control the effects of wind, even when the wind is less than eight miles per hour.

The two fire pit facilities differ in the manner the manikins are moved through the fire. The Natick facility suspends the manikins from a motor driven continuous wire rope. The Johnsville facility employs a pedestal at the side of the fire pit from which extends a long boom supporting the manikin. The manikin traverses a semi-circular path from behind a protective wall, through the fire, and out behind the protective wall. It has been observed that the construction of the Johnsville facility contributes to a thermal overloading of the dummy due to effects from the wall at the side of the pit. The side of the manikin next to the wall always experiences higher heat flux than the other side of the manikin.

TABLE 1. SUMMARY OF TYPICAL AVAILABLE FIRE TESTING TECHNIQUES

Type of Facility	Location (representative)	Intended use of Facility	Environment Produced	Operation Time	Instru-mentation	Estimated relative Cost	Applicability for materials response testing
Furnance	Ijmuiden, Holland	Flame research related to furnace design and fuel	Radiation from hot surfaces and flames	Continuous	Thermometry Calorimetry Radiometry Pyrometry	Moderate to Expensive	No provisions for material testing
Wood Crib	U. S. Forest Laboratory Riverside, Ca.	Ignition studies, flame pattern, flame spread, and mass fire studies	Actual fire, but transient	Limited by fuel supply	Calorimetry Thermometry	Inexpensive to very expensive	Not practical--reproducibility problems, transient effects, and size of crib needed for proper radiation simulation; specimen too complex to get one - dimensional response and not viewable.
Large pool fires	Naval Weapons Laboratory Dahlgren, Va.	Determine effects of fire on full-scale hardware assemblies	Actual fire, but transient	Limited by fuel supply	Thermometry	Expensive	Not practical--reproducibility problems, transients, and complications of obtaining one-dimensional specimen reponse. Specimens cannot be observed.
Large structure fires	Factory Mutual Research Corp., Rhode Island	Study flame spread in buildings, extinguishment	Actual fire, but transient	Limited by fuel supply	Thermometry	Expensive	Not practical--reproducibility problems, transients, and lack of setup to obtain one-dimensional specimen response. Specimens cannot be observed.

TABLE 1. SUMMARY OF TYPICAL AVAILABLE FIRE TESTING TECHNIQUES (Continued)

Type of Facility	Location (representative)	Intended use of Facility	Environment Produced	Operation Time	Instru-mentation	Estimated relative Cost	Applicability for materials response testing
Radiant panel tests (quartz lamps)	Boeing Co., Seattle, Was.	Materials evaluation, ignition	High source temperature radiation, no convection	Continuous	Thermometry Calorimetry Radiometry	Inexpensive	Does not thermodynamically simulate a hydrocarbon fire because radiant source temperature is too high and no convection is present.
NASA fire simulation	NASA, Ames, Ca.	Materials evaluation	Radiant and convective sources fairly well simulated for average fire	Continuous	Calorimetry	Inexpensive	Can be used for material evaluations. Limitations are radiant and convective heat flux cannot be independently varied, and the test specimen cannot be observed.
Room Fires	Underwriters' Laboratories Northbrook, Il.	Fire tests of structural assemblies	Actual fire	Continuous	Thermometry	Expensive	Specimen cannot be observed. Some fluctuation in environment with respect to materials response studies. Specimen setup too complex to ensure one-dimensional response.
Fuel Pit fires*	1. Army-Natick Mass 2. Navy-A.M. Stoll Johnsville, Pa	Testing thermal protective clothing systems	Actual fire, but transient	Limited by fuel supply	Radiometry Heat senstive strips	Expensive	Fire is not reproducible; inadequate instrumentation.

*Table modified from Belason.

In both facilities, fiberglass manikins are used and thermal sensitive paper strips are used as heat detectors. These strips are imprinted with organic chemicals that melt or change color at specific temperature. Waldron et al(11) report that these strips were calibrated at Natick Labs using a solar furnace. There has never been, however, a calibration using these strips in a fuel fire. The chemical effect of fire by-products on these strips is not known. These strips are used to indicate the highest temperature experienced by the manikin. These strips do not provide temperature vs time profile important in estimating physiologic injury. Neither facility has utilized more sophisticated means of data acquisition other than to photograph the fire from several angles. The fire itself is monitored with a radiation calorimeter (Natick) to ensure that the fire has reached its maximum intensity prior to the manikin's entering the fire.

Both the Natick and Johnsville fire pit facilities suffer from two major faults. First, in employing a water pool as a base for the fuel spills both facilities introduce a factor that has been shown to result in a cooler than normal fire. Second, the lack of adequate wind breaks result in fires of great variability; flames move rapidly out of the path of the manikin at the slightest breeze, and fuel/air composition varies due to wind transients. Because of these faults it is impossible to simulate adequately a post-crash fire in an open pit facility.

PART II

THE FEASIBILITY OF REPRODUCING JP-4 FIRES UNDER CONTROLLED CONDITIONS

During the summer of 1970, Enertech, Inc., submitted a proposal at USAARL's request to study the feasibility of duplicating the thermal and chemical environment of a JP-4 "post-crash" fuel fire in a relatively small "furnace". In October, a contract was signed and on 6 November, USAARL received a progress report identifying some of the problems encountered. Enertech felt it was necessary to measure carefully the characteristics of an actual field fire, and late in December a field fire was conducted at Fort Rucker. In January, Enertech submitted their final report, "The Feasibility of Simulating JP-4 Fuel Fire Environments Under Reproducible Furnace Conditions."

The majority of Enertech's report (Appendix 1) is concerned with the theoretical problems of reproducing the worst credible environment that a person is likely to encounter in a JP-4 fuel fire and only briefly concerned with the engineering problems of moving an instrumented dummy or animal through this environment. As a result of the field fire test, Enertech determined that in the worst credible environment, temperatures could be expected in the range of 2000°F to 2200°F. The two principal problems encountered in reproducing such an environment were (1) determining the required air/fuel ratio and (2) providing the same radiative background in the field fire simulation cell as would be encountered in an actual field fire.

The rate at which air enters the furnace determines the thermal and chemical environment of the fire. Enertech calculated the rate at which air must enter the fire, and in their conceptual plan for the furnace provided air blowers and regulators which would supply the air at this rate. The furnace could simulate field fires for fuels other than JP-4 if the necessary air injection rate was determined.

To provide the necessary radiative background, Enertech felt that it would be necessary to have at least three feet of fire on each side of an instrumented dummy or animal as it moved through the chamber. There is some uncertainity in this figure, however, and it might be necessary to heat the blackened walls of the furnace for two or three minutes before sending an instrumented dummy through the fire. The walls could be preheated either by using a combustible mixture sprayed across the walls, or by allowing the fuel to burn from two to three minutes before any test was made.

In considering the proposed field fire simulation cell, the most important technical question is whether it will provide a reproducible fire that approximates the conditions of the worst credible environment likely to be encountered in an actual field fire. The investigation by Enertech indicates that it is possible to approximate the thermal and chemical environment of an actual field fire in the furnace. It is extremely important in comparative testing of various flight suits, however, that the thermal and chemical environment not differ significantly between tests. Since a JP-4 fuel fire is characterized by extreme turbulance, we should not expect that the temperature at a given point remain absolutely constant after a certain time for two different fires. A certain amount of arbitrary fluctuation in the temperature is unavoidable, but probably will not be large.

Other considerations in the design of the furnace such as the way in which the dummy enters and exits the fire, means of moving it through the flames, ways of acquiring data from the dummy, regulation of the fuel supply, and details of the construction appear to be primarily engineering problems which do not pose insurmountable problems in the construction of the cell. Enertech's conceptual plan provides safety measures: in an emergency the fuel may be quickly withdrawn from the furnace and the chamber may be purged with nitrogen; the fuel storage tanks are located below ground at a safe distance from the furnace; and the entire enclosure is surrounded by a protective wall.

PART III

INSTRUMENTATION

Instrumentation for this facility must be capable of providing data of two basic kinds. First, the thermal environment must be monitored to quantitate its severity and reproducibility. Second, the surface of a manikin must be monitored to assess the degree to which it has been protected by the overlying test clothing in the simulated fire environment.

Sensors which monitor the environment and the manikin will be part of a data acquisition system (Figure I). It is anticipated that it will require thermocouples, radiometers and calorimeters to monitor the fire adequately. Thermocouples will monitor the wall temperature of the furnace and flame temperatures along the path of the manikins. Calorimeters will be used to measure total heat flux (radiative and convective) and radiometers will measure radiant heat flux. The difference will give the convective heat flux.

It is clear from the literature(10) that tissue damage depends not only upon tissue temperature but also upon the time tissue remains above the damage threshold. Clearly then, the manikin must be instrumented with thermocouples to give reliable time-temperature data. Since all the tissue damage vs time-temperature data in the literature(10) was derived using either pure radiative loading or flame contact with a meeker burner, it will be necessary to calibrate the response of thermocouple instrumented manikins in relation to the response of instrumented pigs.

The analog data from these sensors will be filtered, amplified, converted to digital format and stored for future analysis. The details of the data acquisition system follow.

Figure I below represents the data train for the facility as contemplated.

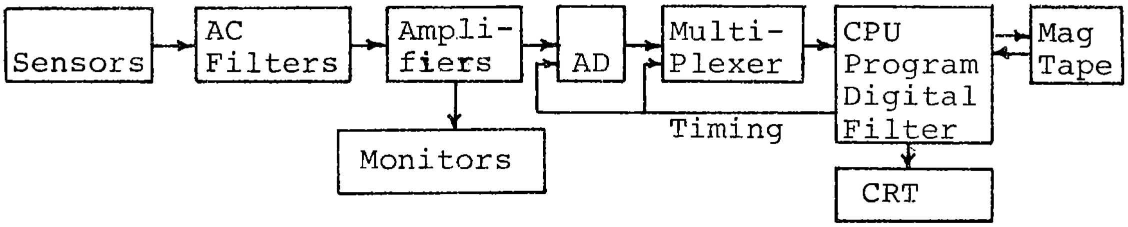

FIGURE 1

BLOCK DIAGRAM OF DATA
ACQUISITION SYSTEM

<u>Sensors</u> - The sensor package will consist of thermocouples, calorimeters, radiometers, and a real time clock (gas sampling sensors will be covered in another section).

<u>Thermocouples</u> - Thermocouples will be used to measure the temperature at 25 locations [based on the DuBois distribution used by Alice Stoll(3)] on the manikin and five places inside the chamber. The thermocouples will be of the large diameter type (probably .032" diameter) to insure ruggedness and long life. Thick thermocouples have slower response times than thin thermocouples, but this problem can be resolved by using a few thermocouples of different thicknesses (all large), and extrapolating the curve back to a zero thickness thermocouple to find the correct temperature(5) (Figure II). Thermocouples may be radiation shielded if a leather artificial skin stimulant(6) is used.

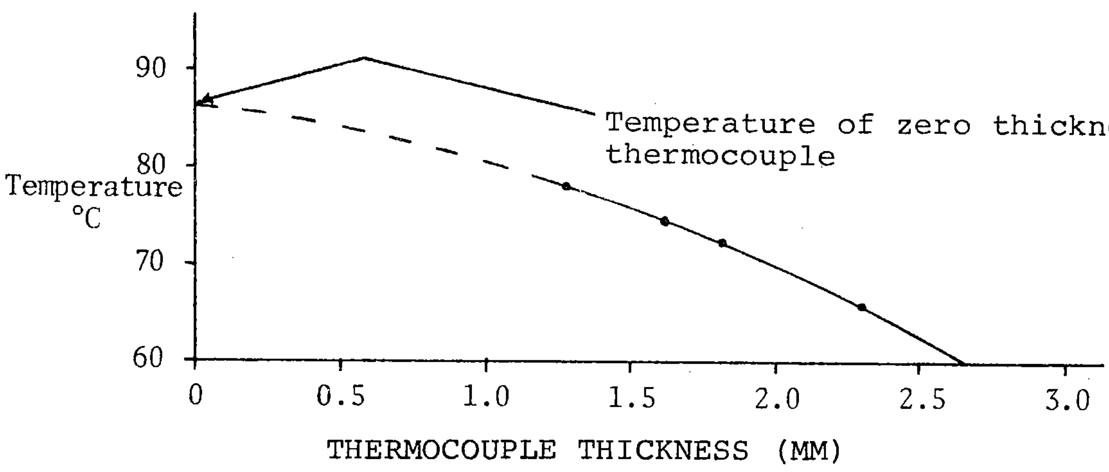

FIGURE II

Plot of temperature <u>vs</u> thermocouple thickness at a specific time.

Calorimeters - Calorimeters will be used to measure the total heat flux present in the chamber and impinging on the manikin.

Radiometers - Radiometers measure the radiative portion of heat flux. Using both radiometers and calorimeters, the convective and radiative components of the heat flux can be calculated. The radiometers will be placed in the same positions as the calorimeters.

Real time clock - A digital real time clock will be used to provide accurate timing for all portion of the systems.

AC Filters - The AC Filters will be three pole low pass filters. The filters will be used to attenuate high frequencies and noise that are extraneous. Approximately 35 AC filters are needed.

Amplifiers- Instrumentation amplifiers (Signal Conditioners) are necessary to increase the millivolt signals from the thermocouples, radiometers, and calorimeters to appropriate voltage levels and impedances for the Analog to Digital converter. One amplifier will be needed for each channel, requiring a total of 35 amplifiers.

Monitors - Monitoring oscilloscopes are included so that the sensors can be measured before and during operation to insure they are working correctly. The monitors insure that a fire will not be run without full instrumentation.

A/D, Multiplexer, CPU Programmable Digital Filter, CRT - The analog to digital converter, Multiplexer, Central Processing Unit, Programmable Digital Filter, and Cathode Ray Tube display, are grouped together because in all likelihood they will be purchased from the same company; their operation is interrelated because of common timing signals.

The A/D unit will convert the amplified signals into an easily manipulated digital format. The multiplexer will then take these digital signals and multiplex them together into one data chain that can be fed into the CPU Programmable Digital Filter. The purpose of the digital filter is to select only the pertinent data which will be of use and to discard data which has no significance.

The digital filter must be programmable for each new kind of test; then the filtering can be changed to fit the nature of the data.

The Cathode Ray Tube Display is included so that an on-line display of information can be obtained. Particular points of interest can be monitored without interrupting the data flow.

Mag Tape - The magnetic tape recorder is the end of the data chain and consists of a magnetic tape device that is compatible with the CPU Programmable Digital Filter.

The cost of the anticipated system is detailed in Table II

Sensors	No.	Prices (each)	Minimum (total)	Maximum (total)
Thermocouples	30	$2- $5	$60	$150
Calorimeters	2	200- 400	400	800
Radiometers	2	200- 400	400	800
Digital Clock	1	600- 1000	600	1000
Cables & Connectors	-	- -	500	1000
AC Filters	35	5- 10	175	350
Instrumentation AMP	35	200- 700	7000	24500
Monitors	2-4	1500- 3000	3000	12000
A/D Multiplexer	1	4000- 7000	4000	7000
CPU Prog Dig Filter & CRT	1	25000-40000	25000	40000
Mag Tape	1	5000-10000	5000	10000
TOTAL			$46,135	$97,600

TABLE II

COST OF DATA ACQUISITION SYSTEM

The data acquisition system will sample and store on tape accurate time-temperature data from 25 locations on the manikins and five locations in the chamber, plus accurate time-heat flux from two locations within the chamber. Radiative, convective, and total heat flux will be available.

The chamber temperatures and heat flux will indicate the reproducibility of the fire. The time-temperature data will be correlated (based on calibration from instrumented pigs) to indicate time-temperature data for skin. Tissue damage will be calculated using the methods of Alice Stoll(10), modified as necessary. This data reduction can be accomplished off-line using the CPU or any small to medium size computer. The following section addresses the problem of gas analysis and is followed by a discussion of data reduction methods.

The preceeding paragraphs have outlined a data acquisition system that will detect, record and analyze various thermal parameters (temperature, convective and radiant heat flux). Emphasis was placed (1) on recording the fire to insure reproducibility and (2) on recording the thermal energy transferred through a flight suit to the surface of a manikin.

Any protection afforded a pilot by a flight suit will be negated if, through inadvertant breathing, the pilot subjects his respiratory system to a toxic mixture of very hot gases. There is some argument among burn experts about the relative hazards of temperature and content of inspired gases. There is little doubt, however, about the serious threat of a fire environment to the respiratory system.

At this time it is not possible to define precisely the threat to the respiratory system; nor is it possible to describe a survivable envelope of gas temperature and content.

The proposed facility could be used to do some much needed research in this area. To allow for this possibility the following gas analysis system is proposed.

In assembling the system it has been assumed that pilot exposures will be less than 20 seconds. (In fact the current garment tests seldom exceed 10 seconds). In addition, the pilot is assumed to take between one and twenty breaths during a twenty second exposure. Realistically speaking, one breath of very hot air may be sufficient to halt further breathing unless coughing occurs.

State-of-the-art CO and CO_2 infrared measuring instruments have time constants on the order of 0.5 seconds. This is sufficient for continuous monitoring during a twenty second exposure but too slow for a three to six second exposure. Paramagnetic O_2 analyzers have time constants of ten to forty-five seconds and, thus, are unsuitable for continuous O_2 measurement during a twenty second exposure.

Gas chromatographs are required to measure N_2, and if used to measure CO, CO_2 and O_2 as well, they will take five minutes to do so.

The response times of gas analyzers and manikin exposure times dictate that a rapid sequence, "grab sample" system be used to collect gas samples for off-line analysis. While an on-line mass spectrometry system of gas analysis offers some advantages, reliable gas collection in this atmosphere is doubtful. Furthermore, the additional cost of $50,000 to $60,000 negates further consideration of such a system. The following table outlines the components of a gas analysis system which is compatible with the data acquisition system (Figure I). These components would be listed in the blocks marked sensors and amplifiers.

COST OF BASIC GAS ANALYSIS SYSTEM

	MINIMUM	MAXIMUM
Gas Sampling & Conditioning System	$ 2500	$ 4000
Infrared CO Analyzer	2000	2500
Infrared CO_2 Analyzer	2000	2500
Paramagnetic O_2 Analyzer	2000	2500
Chromatograph N_2	6000	10000
Signal Conditioners	1200	2800
	$15,700	$24,300

A gas sampling system is not needed to screen garments for thermal protective capability. It is, however, needed to investigate the effect of hot toxic gases on the respiratory system of a pilot.

Data Analysis - A word of Caution

The primary purpose of building the field fire simulation cell is to measure the amount of burn protection offered by various flight suits. It might seem that the most straightforward means of measuring the amount of protection offered by a flight suit would be to clothe an instrumented anthropomorthic dummy in a flight suit and to measure the temperature on the surface of the dummy as it passes through a fire.

Careful consideration, however, indicates that the situation is more complex than might be expected. Three questions that must be answered are: (1) is the measured temperature on the surface of the dummy the same as the actual temperature? (2) is the temperature on the surface of the dummy the same as the skin temperature of a human being in an equivalent situation? and (3) how is the skin temperature related to tissue damage?

If thermocouples are used to measure the temperature on the surface of the dummy, and if the primary mode of heat transfer to the surface of the dummy is convective or conductive, then we may expect that the measured temperature and the surface temperature would differ by only a small amount, and that depending on the response time of the thermocouple. By using thermocouples of various sizes and extrapolating to a thermocouple of zero thickness, we may correct for this response time.(5) If, however, the heat transfer to the surface involved radiative heat transfer, then a number of problems arise.(9) The thermocouple will absorb a different proportion of the radiation from either the dummy or the human skin. If the radiant heat flux were small, then we could neglect the effects of radiation on the thermocouple. Unfortunately, it is difficult to obtain an *a priori* estimate of the radiant heat flux to the surface of the dummy.

The easiest solution to this problem is to cover the thermocouples with a thin leather skin simulant which has thermal and optical properties similar to that of human skin.(2,6) Then, the only mode of heat transfer to thermocouple would be conductive and the problems associated with radiative heat transfer may be neglected.

Once the heat has been absorbed by the leather skin simulant, the equation that determines the temperature at any point below the surface is the heat conduction equation,

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

where T is the change in temperature, t is time, x is the distance from the surface, and α is the diffusivity of the material. If the leather skin simulant has a diffusivity and thickness approximately equal to that of the human epidermis, then we may

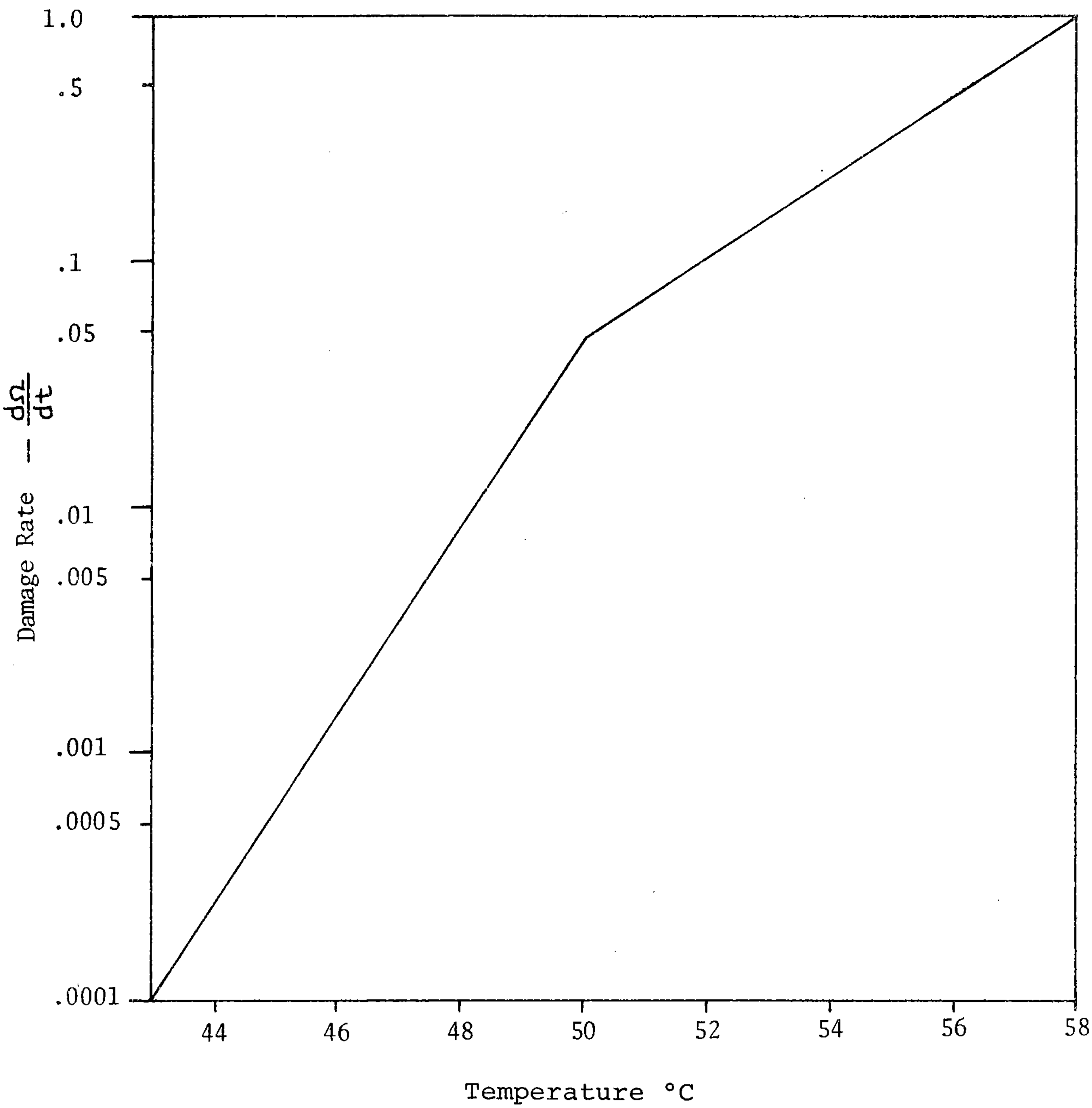

Figure III - Relationship Between Rate of Tissue Damage and Temperature

Using this graph the damage rate, $d\Omega/dt$, may be found if the temperature of the basal epidermal layer of the skin is known. If the total damage, Ω, is greater than 1.0, then transepidermal necrosis has occurred.

expect that the temperature measured by the thermocouple would be the same as the temperature of the human skin. The thermal properties of the fiberglass dummy, however, will also affect the measured temperature. A mathematical model is being developed to determine what effect the thermal properties of the fiberglass will have and how these properties may be corrected. When these corrections are made, the temperature at the base of the human epidermis may be determined from the temperature measured by the thermocouple.

In 1947, Henriques and Moritz(4,7,8) published a series of articles on thermal injury and proposed a relationship between the temperature at the base of the epidermis and the rate of tissue damage. They exposed porcine and human skin to water at carefully controlled temperatures, and determined the amount of time for transepidermal necrosis to occur. Then they theoretically determined the temperature of the basal epidermal layer of the skin and found a relationship between this temperature and the rate of tissue damage. Later work by Alice Stoll and L.C. Greene(10), who used radiant energy as a source of heat, indicated that Henriques and Moritz had failed to account for the damage that occurred as the skin cooled. The slightly modified relationship proposed by Stoll and Greene between temperature and the rate of tissue damage is presented in Figure III. Referring to this Figure, it may be seen that tissue damage occurs very slowly at 44°C (111°F) while the epidermis is destroyed in less than one second if the temperature of the basal epidermal layer exceeds 58°C (135°F). Although there is some question about the accuracy of this relationship, it may be used to estimate tissue damage from the corrected temperature.

From these considerations, it is possible to describe a procedure that may be used to determine the tissue damage a human would suffer. Several thermocouples of various sizes are mounted close to one another on the surface of the manikin and covered with a thin layer of the leather skin simulant. Corrected thermocouple readings take into account the thermal characteristics of the manikin and the simulant. From this corrected temperature, the rate of tissue damage is determined at any given time. By integrating the rate of tissue damage as the manikin moves through the fire, and by allowing for the damage that would occur as the skin cooled, the total tissue damage is determined. In addition to the thermocouples, a radiometer and a calorimeter are mounted on the manikin to determine the radiant heat flux and the total heat flux to the surface of the manikin. A knowledge of the relative proportion of radiant, convective, and conductive heat flux will be invaluable for engineering design of flight suits.

PART IV

MANAGEMENT CONSIDERATIONS

While the preceeding sections have demonstrated that a sophisticated thermal evaluation facility is compatible with the state-of-the-art, a discussion of this matter would not be complete without addressing some of the managerial problems associated with such a facility.

COSTS

It is apparent that construction and instrumentation costs will be high. Current cost estimates are as follows:

COST ESTIMATES

A.	Total funds allocated -	$140,000.00		
	Cost of Phase I -	27,000.00		
	Funds now available -	113,000.00		
			Minimum	Maximum
B.	Cost of basic simulation cell (includes specifications) -		$100,000.00	$125,000.00
	Cost of Instrumentation (includes gas) -		62,000.00	123,000.00
	Administrative and Miscellaneous -		5,000.00	15,000.00
	Sub-Total		$167,000.00	$263,000.00
	First year's operation costs		30,000.00	50,000.00
	TOTAL		$197,000.00	$313,000.00

Past experience has demonstrated that even the best cost estimates are poor when a unique device is to be constructed. It is virtually impossible to predict all the possible problems that may arise. While it is our opinion that all problems can be overcome, the cost of such solutions cannot be predicted in advance.

Once the facility becomes operational, maintenance costs will not be excessive, but they will be significant. Skilled personnel are essential and will be a source of constant expense - whether or not the facility is in use. Maintenance of sophisticated electronic instrumentation will be a source of continual expense. Sensing devices will require a relatively frequent replacement as will fuel and other routine supplies. It is estimated that $30,000 to $50,000 per annum will be a minimum cost necessary to maintain a reliable, responsive facility. Frequent usage would increase this figure significantly but would reduce the cost per unit evaluated.

PERSONNEL

At the onset of Phase II it is essential that two full-time civilian employees be obtained. An individual with training and experience in Mechanical Engineering and Thermodynamics must be obtained immediately. He should be intimately involved in the construction of the facility and be entirely responsible to the USAARL Commander for its management and operation when construction is completed. At a later time, but prior to completion of construction, an individual trained and experienced in Electrical Engineering and Data Processing must be obtained. He will be responsible for maintenance and operation of data collection and analysis systems. These two permanent civilian employees are necessary on a full-time basis. While military personnel with the necessary capability could be obtained, the lack of continuity and experience, as well as conflicting duties, would place reliability and responsiveness at an unacceptable level. Additional assistance will be required other than the two civilian employees and this can be provided by military personnel. If instrumentation maintenance is performed on a service contract basis, perhaps one full-time employee will suffice. This matter will require a policy decision early in the construction phase.

UTILIZATION

Certain policy decisions regarding utilization must be made at this point. If the facility is to be used primarily for operational testing of clothing ensembles and cockpit components, then the emphasis must be upon economy, simplicity, and durability. If, the facility is used to a significant extent for basic and applied research on the biological effects of fires, then the emphasis must be upon flexibility and reliable instrumentation. For example, if the primary interest is to be the measurement of heat flux to skin, then the cost of gas measurement certainly exceeds benefits to be derived. If the facility is to be used to study the effects of fire on other organ systems than the integument, then gas measurement is essential.

In short, we must determine if the facility will be used as a dramatic method of demonstrating fabric characteristics, or if it will be used as a tool for the study of the basic physiology of man exposed to fire. This policy decision will have a significant effect upon instrumentation and cost, and ultimately upon the benefits to be derived from the facility.

LOCATION AND MANAGEMENT

Agreement as to location and command control must be clearly settled. At this point it must be candidly considered that a number of DOD agencies feel a vested interest in a facility like this one. Other agencies have been engaged in fabric evaluation for a prolonged period of time. USAARL, however, has maintained a broad interest in the medical, physiological, and engineering aspects of aircraft fires. The agency which will manage such a facility should build it. All testing of thermal protective garments must ultimately be related to human burn protection. For such testing to be valid, only medical personnel with an operationally oriented bioengineering approach are qualified to make such medical inferences. Such a capability exists in the Bioengineering Division of the US Army Aeromedical Research Laboratory. The facility should be available to all DOD/Federal agencies with a valid need for it. In addition, it should be available to non-government institutions, if the primary mission permits, on a fee for service basis.

The question of modification of an existing facility will, of course, be raised. Since the contemplated facility approaches the problem in a unique manner, none of the existing facilities could be modified to meet the requirements of this facility.
Naturally this facility could be built, at the location of an existing facility but no particular advantage or disadvantage to this course of action is recognized. Wherever such a facility is located, meaningful medical review and correlation, as defined in the preceeding paragraph, is essential. It is desirable, but not essential, that it be located where such a medical capability exists.

MISCELLANEOUS CONSIDERATIONS

The provisions of Public Law 91-190 regarding air pollution require consideration. While this consideration is not likely to present a major problem, it is possible that administrative delays may result.

Fire and explosion safety have been considered in design but will require administrative approval and could conceivably cause delay in beginning construction.

PART V

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. It is reasonably technically feasible to construct a facility which can uniformly reproduce the conditions found in a JP-4 fire.

2. It is possible to utilize information obtained from exposure of clothing ensembles to such a fire to predict probable human burns which would occur if a human were exposed to the same conditions.

3. The cost of such a facility will be high and justifiably dependent upon intended utilization.

4. Information derived from operational testing in such a facility would not provide an order-of-magnitude improvement in current methods. We believe that the cost of a facility for purely operational testing exceeds the recognized benefits to be derived.

5. It is essential to obtain a full-time civilian employee at this time and an additional employee prior to completion of the facility.

6. Certain policies must be clearly established prior to implementation. Information has been provided to form the basis for these decisions.

7. The facility cannot be constructed in accordance with original time schedules.

SOME ALTERNATIVES

Some of the recognized alternatives are listed, not necessarily in order of preference.

1. Proceed as originally planned, building a facility as designed by Enertech and:

   a. Minimize costs and use purely as a demonstration/test device.

   b. Maximize flexibility and reliability and plan to use facility for both research and testing.

2. Discontinue project and:

a. Further develop bioassay method developed at USAARL by Knox et al.

b. Attempt to build semi-open fire pit designed to decrease wind effects, eliminating effects of water pool and using current methods of Waldron et al for quantification.

c. Utilize current facilities and methods.

RECOMMENDATIONS

The wisdom of constructing a fuel fire simulation cell has not been clearly established. Because of the high cost, the multitude of bioengineering complexities and problems, and because far less expensive laboratory methods produce much of the data that would be provided by the simulation cell, USAARL does not consider construction of the facility at this time to be a prudent expenditure of public funds. Further evaluation of less expensive bioassay methods and better biomedical correlation of existing methods are considered more reasonable approaches. Continued development of Phase II & III, as currently conceived, is not recommended. If further development of this program is pursued, however, a sophisticated medical input by qualified operationally oriented bioengineering personnel is essential.

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APPENDIX I. ENERTECH REPORT

THE FEASIBILITY OF SIMULATING JP-4 FUEL FIRE ENVIRONMENTS UNDER REPRODUCIBLE FURNACE CONDITIONS

January 1971

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THE FEASIBILITY OF SIMULATING JP-4
FUEL FIRE ENVIRONMENTS UNDER
REPRODUCIBLE FURNACE CONDITIONS

Prepared for: The Life Support Branch of the
Bio-engineering Division
U.S. Army Aero-Medical Research Laboratory
Fort Rucker, Alabama

January, 1971

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ABSTRACT

This report presents the results of a study to determine the feasibility of simulating, within an enclosure, the thermo-chemical environment which exists in a JP-4 fuel fire following the crash of an aircraft.

Present comparative testing techniques of the protection offered by various garments suffer from the inability to accurately reproduce the fire environment from test to test either because of uncontrollable variables such as wind speed and/or severe alteration of the air entrainment requirements of an actual field fire. Establishment of the feasibility of reproducible comparative testing within an enclosure, considerably smaller in size than an actual field fire, requires determination of

- Those variables which influence the fire thermal and chemical environment.
- Definition of the Worst Credible Environment likely to be encountered.
- Development of an analytical model, capable of predicting a field fire thermo-chemical environment, which can then be used to determine the requirements of an enclosed facility which will reproduce this environment.
- A conceptual design which integrates the theoretical requirements of an enclosed fire facility with the thermal and structural limitations of existing construction materials.

These tasks were successfully accomplished and detailed results are presented in this report. Based on these results it has been concluded that an enclosed fire facility for comparative garment testing is feasible

LIST OF FIGURES

(All figures are located at the end of their respective chapters)

NOMENCLATURE FOR CHAPTER VII

h_c	Convection heat transfer coefficient
I_ν	Monochromatic intensity
$I_{b\nu}$	Planck's Black Body intensity
$I_{w\nu}$	Wall intensity
k	Thermal conductivity
ℓ	Radiation path length
Q_c	Convection heat flux
Q_R	Radiation heat flux
Q_T	Total heat flux
s	Plate thickness
t	Time
T_F	Fire temperature
T_i	Initial temperature of wall
T_w	Instantaneous wall temperature

Greek

α	Thermal diffusivity
ν	Subscript denoting frequency
κ_ν	Radiation absorption coefficient

I. INTRODUCTION

The crash of an aircraft may involve spillage of fuel from ruptured fuel tanks and fuel lines. A frictional or electrical spark or heated surfaces can cause the spilled fuel to ignite. If the pilot or crewmembers of such a crash are not immobilized they may have to seek escape through the flaming fuel and the degree and extent of burns they receive will depend upon the thermal protection provided by their garments. The need for comparative testing of the protective qualities of various garments is therefore evident. However, because of the uncontrollable nature of the wind speed and direction, comparative testing of garments in large open fires is not likely to be reliable, except on a statistical basis which would require a large sample of tests and would, therefore, be expensive. Thus, the concept of an enclosed fire naturally arises and the Enertech Corporation of New York was contracted to undertake a study to determine the feasibility of constructing a Field Fire Simulation Cell (FFSC) which would enable meaningful comparative testing of the fire protection offered by various garments. The object of this work was to define the requirements of an FFSC and to recommend a conceptual design which would provide the necessary thermochemical environment for comparative testing.

The requirements of an enclosed fire facility are that

- It create a fire environment consistent with that encountered in a field fire following an aircraft crash.

- It be capable of providing this environment on a consistently reproducible basis.

It is obvious that JP-4 or other fuel can be burned in an enclosure. However, the temperature, chemistry and heat transfer to an instrumented manikin clothed in the test garment will be far removed from actual field conditions unless care is taken to provide the proper rate of air injection into the fire and heat transfer from the fire. This is confirmed by the fact that adiabatic flame temperatures for hydrocarbon fuels, undergoing complete reaction with stoichiometric proportions of air, range between 4000 and 5000°F, whereas measured temperatures in open JP-4 field and laboratory fires range between 1500°F and 2400°F. These lower temperatures, characteristic of field fires, are the result of incomplete combustion and heat losses to the environment. Therefore, regulation of air supply to the FFSC and the control of heat transfer from the flames required a detailed examination before the feasibility of simulating field fire conditions could be established.

The technical details of this program, along with its conclusions and recommendations, are presented in the succeeding chapters of this report.

II. SUMMARY

A combined experimental and analytical program was established to determine the feasibility of simulating in an enclosed fire test cell (FFSC), the field fire environment following an aircraft crash. This program consisted of

- Reviewing previous studies of crash fires to establish the thermo-chemical environment to be expected following an aircraft crash characterized by

  (i) high probability of impact survival and

  (ii) high fire risk.

- Supplemental experiments to provide data not available in the published literature.

- Development of an analytical model, consistent with field test data, which would be suitable for establishing the requirements of an FFSC.

- Conceptual design considerations which would result in a facility capable of providing the theoretical requirements for simulation of crash fire conditions.

It was clear from the initiation of this feasibility study that many variables present in an actual field fire resulting from an aircraft crash were of a random nature and could not be meaningfully simulated in either open field or FFSC testing. Included among such random variables are

- Wind speed
- Wind direction
- Nature and extent of fuel spread and/or spray
- Terrain topology
- Nature of the soil and/or foliage in the vicinity of the fire
- Degree of protection offered by the cockpit before the pilot emerges into the flames
- Time for pilot to react to fire environment

All of the above variables are beyond the control of the experimenter in a field fire. Nonetheless, they determine the nature (temperature, chemistry, etc.) of a specific fire or the degree of injury sustained. An FFSC could be built which provides flexibility for adjusting these independent (input) variables, but there is no a priori basis for their prescription due to their random nature under actual field conditions. An early, fundamental, decision was therefore made to avoid simulating these variables. Instead, since it is the relative fire protection offered by various garments that is of importance, it was decided to seek a definition of the worst, but realistic, fire environment to which a pilot or crewmember might be exposed. This condition is referred to as the Worst Credible Environment (WCE).

In order to establish the WCE, a thorough literature survey covering aircraft fires and aircraft fuel fires was undertaken. This material is discussed in Chapter III, but the inconclusiveness and contradictory evidence to be drawn from the various references required the performance of a large field test by Enertech in cooperation with the U.S. Army Aero-Medical Research Laboratory at Fort Rucker, Alabama on December 21, 1970. This test is described completely in Chapter IV. The main conclusions from the literature survey and field test were :

- The fire transient is on the order of 20 seconds and, as explained below, the period of greatest interest for this study is from 20 - 50 seconds ("steady state" period).

- The fire temperature gradient near the liquid pool is very large (on the order of 1000°F per foot) and a maximum "steady" temperature of 2000 - 2200°F is reached at approximately two feet.

- Over the remaining height of interest (up to 10 feet) the temperature does not change markedly, i.e., from two feet to ten feet above the pool the fire is virtually isothermal.

- Transverse temperature gradients are small except near the fire periphery where the temperature is lower than in the core. (Within the first six inches the peripheral temperature may be slightly higher than the core temperature.)

- Radiant heat losses to the surrounding environment of the fire are sizeable and cannot be neglected in the analytical prediction of the flame temperatures.

- Pool fires performed on a water base tend to have resultant temperatures lower than actual dry ground field fires.

On the basis of this information, the thermal description of a WCE was formulated. Since fire temperatures during the transient period (first 20 sec.) are less than the "steady" temperatures and since a crash victim cannot start running at time zero, i.e., when the fire starts, the temperature for WCE was taken as the "steady state" distribution. Likewise, because the extent of the actual crash fire cannot be predicted *a priori* and because running speed may be influenced by the nature of injuries sustained during the crash, the cooler fire periphery was neglected in the definition of the WCE. Rather than account for transverse temperature variations near the fire periphery and variable running speeds, it was decided to allow the fire exposure time of the manikin in the recommended FFSC to be a pre-set variable from 3 to 30 seconds.

In addition to the thermal description, it was necessary to prescribe the chemical environment in the WCE. No detailed chemical composition of fires was available and it was not feasible to measure composition in a field fire. However, it was found that for fires above a liquid pool the flames are oxygen deficient in the "steady state" period, whereas if the fuel is sprayed as droplets or a mist and ignited under crash conditions, the mist will be fuel lean and larger temperatures may be achieved. However, the mist is quickly consumed, burning for only approximately 20 seconds after ignition. Mist fires have not been considered in this report since their occurrence is unpredictable and they can be expected to last for no more than 20 seconds. During this period of time, the pool fire is in the transient phase and some cockpit protection is probable. Therefore mist fires do not contribute to the WCE.

The deviation of actual flame temperatures from the adiabatic flame temperature, as mentioned earlier, is the result of heat losses to the surroundings and non-stoichiometric combustion. Furthermore, the burning of an object or garment in a fire is influenced by the environment it "sees," i.e., the local fire temperature <u>and</u> chemistry. Merely providing temperatures and heat fluxes which simulate those of a field fire, as could be done in a radiation furnace, would therefore be unacceptable. (Such furnaces are acceptable only for testing temperature responses of non-combustible objects.)

In order to establish the fire chemistry which would be required in the FFSC, an analytical model which accounts for the chemical, thermal and hydrodynamic behavior of the field fire was developed. This model, developed in Chapter V, incorporates the experimentally determined fire temperature and, in addition, describes the major chemical components of the plume gases. An analysis was then performed on the FFSC to determine the air injection rate required to establish the temperature and chemistry of the WCE.

The heat exchange from the flames to the FFSC walls was found to be quite different from the heat exchange between a field fire and its cold surroundings. A careful study of the influence of the cell walls on the fire environment was therefore undertaken. Theoretical considerations leading to a specification of the wall requirements are discussed in Chapter VII and these requirements were incorporated into the proposed FFSC conceptual design.

The heat transfer rate between the fire and FFSC walls will be different than between a field fire and its environment. With this adjustment the analytical model then allowed for the determination of the air requirement in the FFSC.

Additional details pertaining to the entrance and egress of the manikin, the proper base on which to prepare the JP-4 pool and fire extinction were then considered before arriving at an FFSC conceptual design. This design will enable all of the essential aspects of the WCE to be established in the FFSC on a reproducible basis.

III. REVIEW OF RELATED FIRE TESTS AND FIRE LITERATURE

Literature concerned with experimental programs dealing with aircraft crash fire simulation has been reviewed and quantitative results necessary for FFSC design recommendations were found to be scarce. The most important qualitative and quantitative results for purposes of this study are reviewed in this chapter.

A. CRASH FIRE SIMULATION TESTS

During a major crash, an aircraft is subjected to highly disruptive forces. Mechanical and structural failure of fuel tanks and hydraulic systems may occur, causing release of fuel or other flammable liquids. Fuel spillage can occur in one of three modes:

- Liquid
- Mist
- Carbureted fuel vapor-air mixture

Liquid spillages normally take place when the aircraft has come to rest and fuel spills onto the ground where it may be absorbed, remain in pools or run down slopes of the terrain. Mist or droplet flow spillages occur when liquid spilling from broken fuel lines and tanks is dispersed into liquid droplets by the combined pressure and viscous forces of the air surrounding the aircraft. Because of drag effects, the mist environment moves with the aircraft as it slows down leaving a trail extending downwind of the liquid spillage location. Carbureted fuel vapor-air mixtures are spilled by damage to the engine induction system. This kind of spillage is usually of little consequence because the small amount of mixture present at the time of the failure only causes a detonation effect comparable to a strong engine backfire. This type of failure is important, therefore, only insofar as it can cause ignition of liquid or mist spillages.

The bulk of the information obtained during this feasibility study deals primarily with experiments conducted for full-scale crashes of transport and cargo type aircraft. The pioneer work of Pinkel, Preston and Pesman[1,2] of the NACA Lewis Flight Propulsion Laboratories during 1949-53 provided valuable data on the initiation and growth of aircraft fires. These crashes were considered to be within the range likely to provide a high probability of impact survival but maximum fire risk. The distribution of airborne fuel mist and liquid spillages were studied in detail. It was found that, in general, the progress of the fire after ignition of the fuel depends on the location of the fuel source, the distribution of the fuel spillage prior to initiation of the fire, the wind magnitude and direction and the topology of the local terrain. Generally, the first fuel to ignite is the mist envelope which may surround the aircraft. Flame propagation speeds in the mist may be as large as 70 feet per second. However, the duration of the mist fire is only on the order of 20 seconds, during which time the fuel on the ground has ignited. The flame propagation speed through the fuel on the ground is much slower, especially in the direction opposite to the wind direction.

Prior to ignition, combustible air/fuel mixtures of ground spill fuel would be expected only in the region close to the ground. In the abovementioned crash simulation experiments, a combustible vapor detector was used to determine the thickness of the combustible fuel-air vapor layer above the ground. Generally, the above ground height of the combustible mixture was approximately six inches, but varied in an inverse manner with wind velocity. The height of the combustible mixture, prior to ignition, was found to be higher in the presence of nearby obstructions, acting as walls to shield the pool from wind. This stratification of fuel/air ratio above the liquid pool, which is influenced by the presence of walls, is important only in the first few seconds of the fire, but can cause discrepancies between field fires and FFSC fires during the early stage of the fire transient. This, however, does not influence the choice of the WCE.

Following the work done by NACA Lewis Flight Propulsion Laboratories, several additional simulated crash fires were performed by independent agencies.[3,4] However, the main purpose of these investigations was the development of fire fighting equipment and little attention was given to the details of the thermo-chemical environment and its impact on pilot survivability. In 1957 efforts to develop numerical representations of a fire environment were undertaken.[5] And, in 1960, on the basis of work reported in [5] a series of tests were performed to obtain basic temperature and heat flux (irradiation) data in JP-4 pool fires. Tests with fuel spilled on dry ground and tests with fuel on several inches of water were performed. The purpose of the water bed was to assure complete fuel coverage of the fire base area. Though this is unrealistic from the viewpoint of an actual crash-fire situation, it does provide a degree of reproducibility which is essential either for obtaining thermal data or comparative testing. However, it is to be expected that the presence of a water base will certainly influence the fuel vaporization rate and thereby the thermo-chemical nature of the fire.

The purpose of the investigation reported in ref. [6] was to obtain fire temperature and irradiation data to serve as input data in an analog fire model which was to be used for predicting the temperature response of metallic, non-combustible objects. Temperatures, as a function of position and time, were measured. However, because the thermocouples were attached to 1-inch-square, 1/16-inch thick steel plates, the thermocouple response time was much poorer than for bare thermocouples. This had the advantage of "dampening" the effect of random temperature fluctuations but also invalidates the data during the fire transient. Steady state fire temperatures between 1500°F and 2100°F are reported. An "average" temperature for JP-4 fuel fires of 1850°F is recommended in ref. [6]. However, this must be interpreted not solely in terms of actual fire temperatures but also in terms of heat fluxes. 1850°F is the temperature of an equivalent black body radiating at the rate of 49,000 BTU/hr-ft^2, which is consistent with the measured values ranging from 35,960 to 47,540 BTU/hr-ft^2. On the basis of Bader's results, the Sandia Corp. developed a radiant heating facility for studying the effects of a high temperature JP-4 thermal environment on materials and components. This facility, described in ref. [7], produces an "average" thermal environment which results in 49,000 BTU/hr-ft^2 from an equivalent black body source at 1850°F. However, since no fuel is actually burned, the chemical environment of a JP-4 fire is not simulated and this facility is therefore not suitable for testing combustible materials. It should be mentioned that in ref. [7] maximum JP-4 fire temperatures as high as 2500°F were quoted.

In 1965 JP-4 tests were conducted by Gordon and McMillan for the U.S. Naval Weapons Facility.[8] Their fires were on a liquid base 12 ft x 24 ft and water was added continuously to maintain the fuel surface at a fixed level. Their maximum reported temperature is 1700°F, which seems to further confirm that a water base serves to reduce the fire temperature, especially since the effect of adding cold water to maintain the fuel level constant is to require more of the heat incident on the fuel surface to go into sensible heating of the water as opposed to vaporization of fuel. Gordon and McMillan also attempted to determine the effect of introducing a large, initially cold, body into the fire. Though their results are inconclusive, the introduction of a $1\frac{1}{2}$ ft. diameter x 9 ft. long cylinder into the fire apparently had no measurable effect on the gross fire temperature.

In 1967 tests reported by Waldron, et al [9] were conducted to evaluate the effects of simulated aircraft crash fires on garments at the U.S. Army Chemical Center, Maryland, which led to the design and operation of a fuel fire facility at the U.S. Army Natick Labs (NLABS) for the purpose of achieving a more sophisticated evaluation of the fire protection qualities of garments than was previously possible. Experiments performed at this facility and its description are reported in ref. [10]. This facility uses a water bed for the JP-4 fuel and thus suffers the same limitations reported above. In addition, the presence of a vertical wall at one end of the pool and low level wind obstructions around the remainder of the pool influences the behavior of the fire. The wall was provided to prevent preheating of the clothed manikin before its introduction into the fire through swinging doors in the wall. However, it can cause a severely asymmetric flame envelope. The flames near the wall can be high (well above the head of the manikin) while in regions removed from the wall they can be much lower, often not covering the manikin. In addition, random wind effects cannot be eliminated. As a result of these factors, the manikin occasionally emerges from the fire virtually unscathed or with little burning above the waist. The difficulty of obtaining reliable comparative tests of the fire protection qualities of garments is therefore evident.

In order to establish the temperature distribution in a full scale, dry ground JP-4 fuel fire Enertech, Inc. conducted a simulated ground spillage test in cooperation with the U.S. Army Aero-Medical Research Laboratory at Fort Rucker, Alabama on December 21, 1970. This test and the results obtained from it are presented in Chapter IV.

B. RELATED STUDIES

In addition to full-scale crash fire simulation tests, the literature was searched for information related to the development of an analytical model for the field and FFSC fires. Some of this work is not specifically for JP-4 fuel fires, but is of a more universal nature and is suitable for fire modeling in general. Other information was sought as a specific supplement to the analytical model reported in Chapter V.

Emmons[12] and Hirschfelder[13] present survey discussions addressed to the general problem of modeling diffusion fires. The complex coupling between the hydrodynamic, thermal and chemical mechanisms in a fire is stressed and it is demonstrated that although the equations governing the behavior of fires are known, much auxiliary data required for implementation of solution schemes is lacking. For example, the basic problem of establishing a suitable interface condition between the liquid pool of fuel and the fire above it has not been resolved. Because this information is lacking, empirical burning rate data must be used in any solution scheme.

Spalding[14] discusses the scaling requirements of fire models and shows that the strict requirements of similarity theory are so numerous and restrictive that complete modeling of all fire processes is practically impossible. Fortunately, complete similarity between a JP-4 field fire and FFSC fire is not required; introduction of the concept of a WCE eliminates the need for transient considerations and requires only that the local fire temperature and chemistry be simulated.

The earliest attempts to analytically describe the hydrodynamic, thermal and chemical features of a fire plume are presented in the works of Nielsen and Tao[15] and Morton.[16] Though the method of treating air entrainment in reference [15] is subject to question, the primary limitation of the approach is that it requires a priori knowledge of exactly what chemical constituents are in the products of combustion. Morton[16] stresses the hydrodynamic aspects of fire plumes and though his entrainment model is more satisfactory than that of Nielsen and Tao, he completely neglects detailed chemical considerations.

It is also important to note that both of these analytical treatments were intended for large fire plumes (on the order of thousands of feet in height) and the results are intended only to give representative average values of fire properties. No claim can be made regarding local accuracy which, of course, is a requirement of the present work. Though references [12-16] are not directly applicable to the fire situation reported herein, they did provide some impetus for the analytical model reported in Chapter V. Of greater use in supplementing this analytical model is the experimental data of references [17-22]. In references [17-20] data is presented for the burning rate of representative hydrocarbon fuels including JP-4. Emmons[17] offers some insight into the details of the mechanism by which the fire vaporizes fuel from the pool to maintain itself. However, these tests were performed using pool diameters of 10 inches and less. In references [18] and [19] data for large diameter pools is reported and is applicable to the analysis of the FFSC. The results of ref. [18] correlate well when the liquid regression rate is plotted against the ratio of heat of combustion to heat of vaporization (see fig. 3 of ref. [18]). For JP-4 a burning rate of 4mm/min is obtained from refs. [18] and [19]. Indirectly, it can also be deduced from ref. [18] that the dominant contribution to the irradiation of a surface in the fire flames comes from a region within two feet of the surface. This is in agreement with the statement in ref. [8] that 95% of the irradiation on a surface in a luminous flame comes from a region within two feet of the surface. This result will be referred to again in Chapter VII where the surfaces of interest are the FFSC walls and the garment on the manikin.

Reference [21] is concerned with radiant and convective heat transfer effects at surfaces within the fire and ref. [22] presents details regarding the relevant radiation parameters associated with soot for purposes of establishing radiation heat transfer in luminous flames. Unfortunately, _a priori_ knowledge of the volume fraction of soot is required to apply the results, but some qualitative effects can be deduced. Neill et al[21] obtained values for the irradiation in JP-4 fuel fires which are somewhat lower than the values reported by Bader.[6] However, this may be attributable to the fact that he used nozzle clusters rather than a pool of fuel to supply the fuel to the fire. In addition, for luminous flames, the authors[21] determined a convection heat transfer coefficient of 4 BTU/hr-ft^2-$^\circ$F. This is in agreement with Bader's statement that convection heat transfer in flames is small compared to radiation heat transfer.

IV. RESULTS OF JP-4 DRY GROUND FIELD FIRE TEST

In reviewing the literature pertaining to full-scale JP-4 fuel fires, it was established that although many careful field tests had been performed by other investigators (refs. [1-8]), they all suffer from at least one of two deficiencies from the viewpoint of establishing the WCE. These two deficiencies are

1. Unreliable transient data
2. Use of a water base

The need for reasonably reliable transient data is not to establish the transient that the FFSC should match. Rather, it is to determine whether or not there can be a significant overshoot of the long time (more than one minute) fire temperatures for a substantial portion of the transient period. This information is, of course, necessary to establish the WCE.

Use of a water base, as discussed in Chapter III, can be expected to reduce the rate of fuel vaporization compared to the evaporation rate from dry ground. This will reduce the measured fire temperatures and thereby lead to an underestimate of the WCE.

Because of these two deficiencies in data derived from previously performed tests and the resultant uncertainty in specifying the WCE, it was necessary to perform a field test which avoided these limitations. 500 gallons of JP-4 fuel were spread over an 18'x30' area lined entirely with a canvas. The purpose of the canvas was to prevent seepage of the fuel into the ground before ignition and during the early phase of the fire. Though approximately half of the fuel leaked through holes and seams in the canvas and though the fuel base was not perfectly horizontal, care was taken to assure complete coverage of the test area by not less than ½ inch of fuel prior to ignition. Temperatures were measured at six locations in the fire by 30-gauge chromel-alumel thermocouples. The thermocouple wires were sheathed in 1/16 inch O.D. stainless steel with only the measuring junction exposed to the fire. These thermocouple probes were supported on two field assembled rakes identified as A and B in fig. IV-1. The two thermocouple rakes were identical and were constructed from three 3/4" schedule 40 galvanized pipe sections. The pipe sections were joined by Tees and the thermocouple probes protruded through 1/16 inch holes drilled through plugs in the central opening of each Tee. The thermocouple wires were run inside the pipe to a distance one foot below ground level where each pair was joined to copper wires. Ice was packed around these buried junctions to provide a $32^{O}F$ reference. The bundle of 12 electrically insulated and shielded wires were then buried in a trench approximately one foot beneath the surface. This trench was about 100 feet long, extending to the instrumentation trailer provided by the U.S. Army Aero-Medical Research Laboratory. Here the six copper wire pairs were connected to a model 5801 six channel strip chart milli-volt recorder. The actual locations of the thermocouple rakes during the test is shown in fig. IV-1. Thermocouples 1,2 and 3 were supported by rake A, and 4,5 and 6 by rake B. The height above ground of the thermocouple measuring junctions were 75" (3 and 6) 49" (2 and 5) and 23½" (1 and 4).

In addition to thermocouple measurements, temperatures were also measured using a Pyro optical pyrometer located at positions P1 and P2 in fig. IV-1. For the dimensions involved (18'x30') the fire can be expected to behave as a black body as far as radiation to the surroundings is concerned.[6,11] The pyrometer therefore served to establish the effective fire temperature for radiation heat transfer calculations. It also provided a means of rapidly scanning the fire temperature field to provide further information on transverse and vertical temperature variations.

Throughout the instrumentation assembly, 35mm slide pictures were taken of various components and assembly techniques. In addition, a Miligan motion picture camera (500 frames per second) was provided for film coverage of the fire events over a 4½ minute period following ignition.

The fire was ignited in the immediate vicinity of rake B and although there was a preferred propagation in the wind direction, the flames spread rapidly over the entire pool of fuel. The effect of the wind on the initial fire transient is observed by noting in figs. IV-2 and IV-3 that the response of the thermocouples of rake A lagged behind those of rake B. Eventually, all of the thermocouples were engulfed in the flames. As expected, thermocouples 3 and 6 (nearest to the ground) responded most rapidly showing temperature rise rates on the order of 350°F per second, four seconds after ignition. As expected, thermocouples 2 and 5 (mid-height) lagged behind the bottom thermocouples (3 and 6). Also, thermocouple 1 lagged behind number 2, but for the first few seconds it appeared that thermocouple 4 was leading number 5. This is attributed to the fact that channel number 5 of the recorder could operate oscillation-free only on the 10 mv/division scale, thus showing different sensitivity and response characteristics compared to channel number 4 which operated (as did 1,2,3 and 6) on the 2 mv/division scale. However, after 7½ seconds, the expected transient vertical temperature variation can be observed.

Instantaneous peak temperatures between 2300°F and 2390°F can be observed in figs. IV-2 and IV-3. However, after the initial transient, which lasted approximately 20 seconds, a "steady" temperature of approximately 2100°F is recorded for the next 25 seconds. The variation from one thermocouple to another during this period is not severe. It can be concluded from these results that, except possibly near the edge of the fire, severe temperature gradients do not exist within the flames, i.e., the temperature of the WCE is virtually uniform at 2100°F.

Pyrometer readings were taken from two positions (P1 and P2 in fig. IV-1) during the first 90 seconds of the test. These readings provide representative "steady" fire temperatures. From position P1 the pyrometer was aimed at thermocouple number 5 prior to ignition. As detected by the pyrometer in position P1 the fire temperature 49" above ground was 2090°F. The entire fire was quickly scanned from position P1 and appeared to be at a uniform temperature except at heights less than two feet above ground, where a reading of 1990°F was obtained. From position P2 the fire again appeared to be at a uniform temperature, the indicated value being 2100°F. Since the optical path through the fire when seen from position P2 was approximately 1.67 times as large as from P1, the agreement between measurements made from these two positions confirms that the fire behaved as a black body radiation source. Finally, although local transients could not be measured, the pyrometer readings support the validity of the thermocouple measurements.

THERMOCOUPLE RAKE

A		B	
T.C N°	HEIGHT (INCHES)	T.C N°	HEIGHT (INCHES)
1	75	4	75
2	49	5	49
3	23½	6	23½

PYROMETER READINGS

#	LOCAT.	HEIGHT (INCHES)	TEMP. (°F)
1	P1	49	2090
2	P1	23½	1990
3	P2	ALL	2100

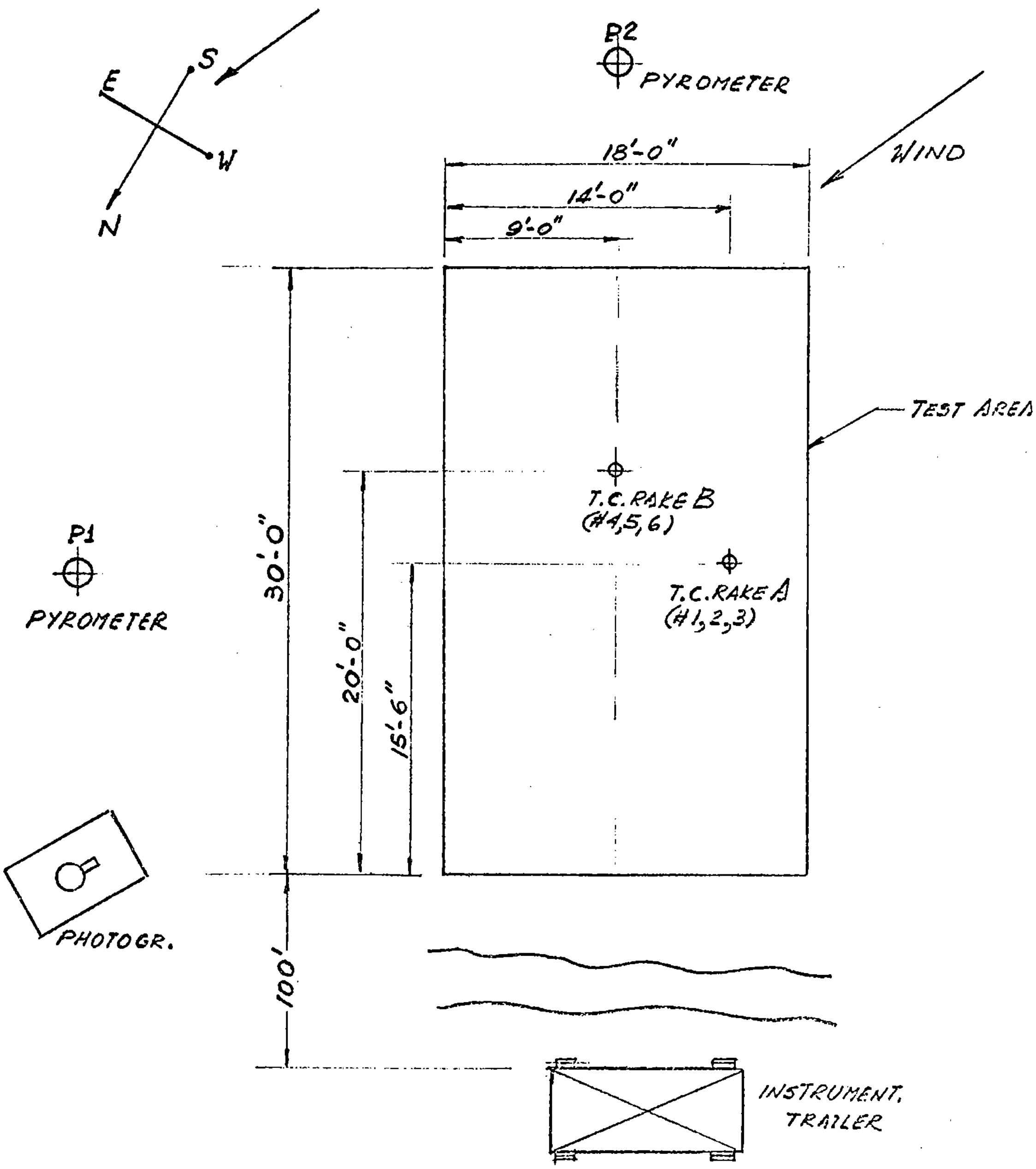


Figure IV-1. JP-4 Field Fire Test Layout, December 21, 1970

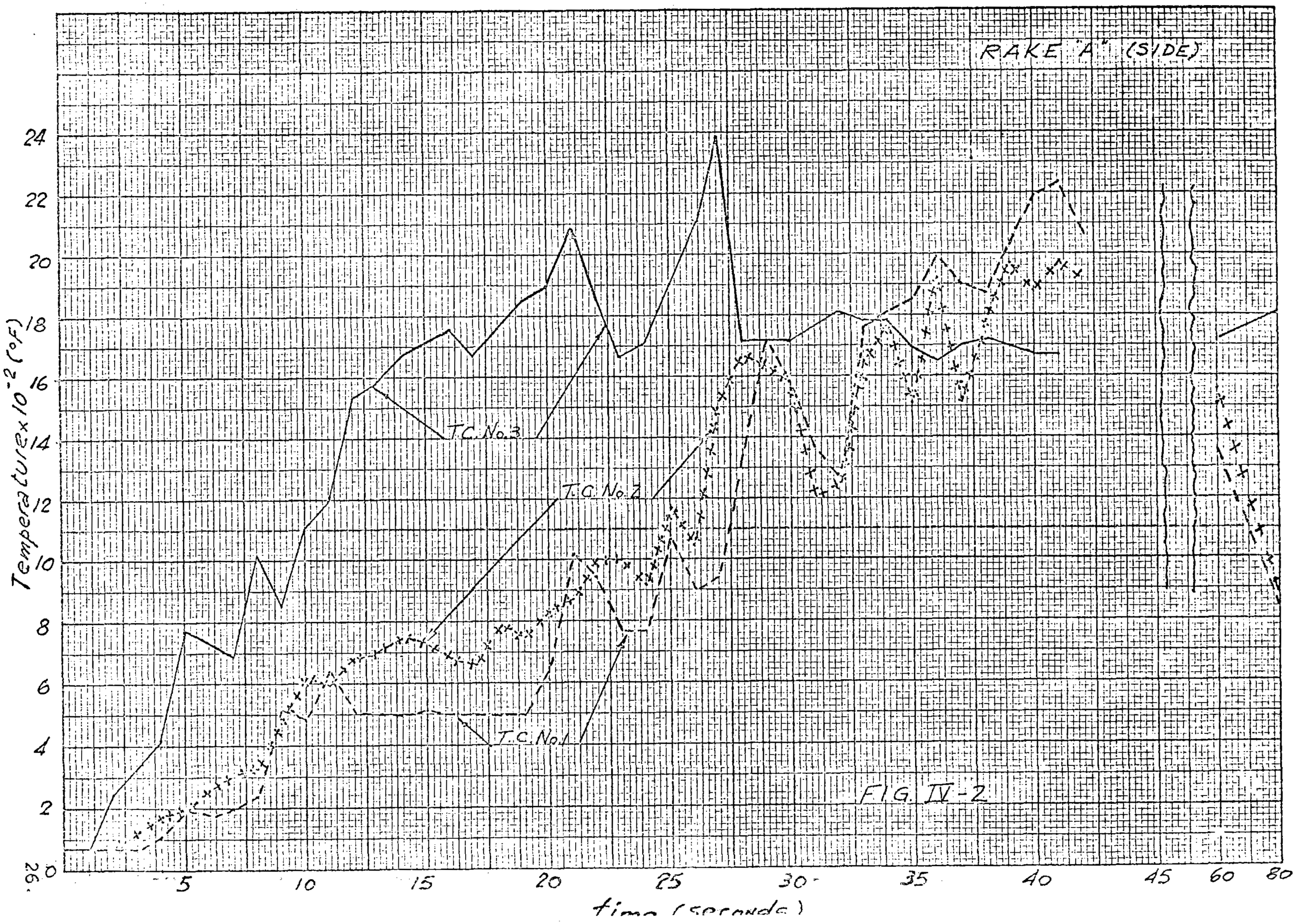

RAKE "A" (SIDE)
T.C. No. 3
T.C. No. 2
T.C. No. 1
Temperature x 10^{-2} (°F)
24
22
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
35
40
45
60
80
time (seconds)

FIG. IV-2

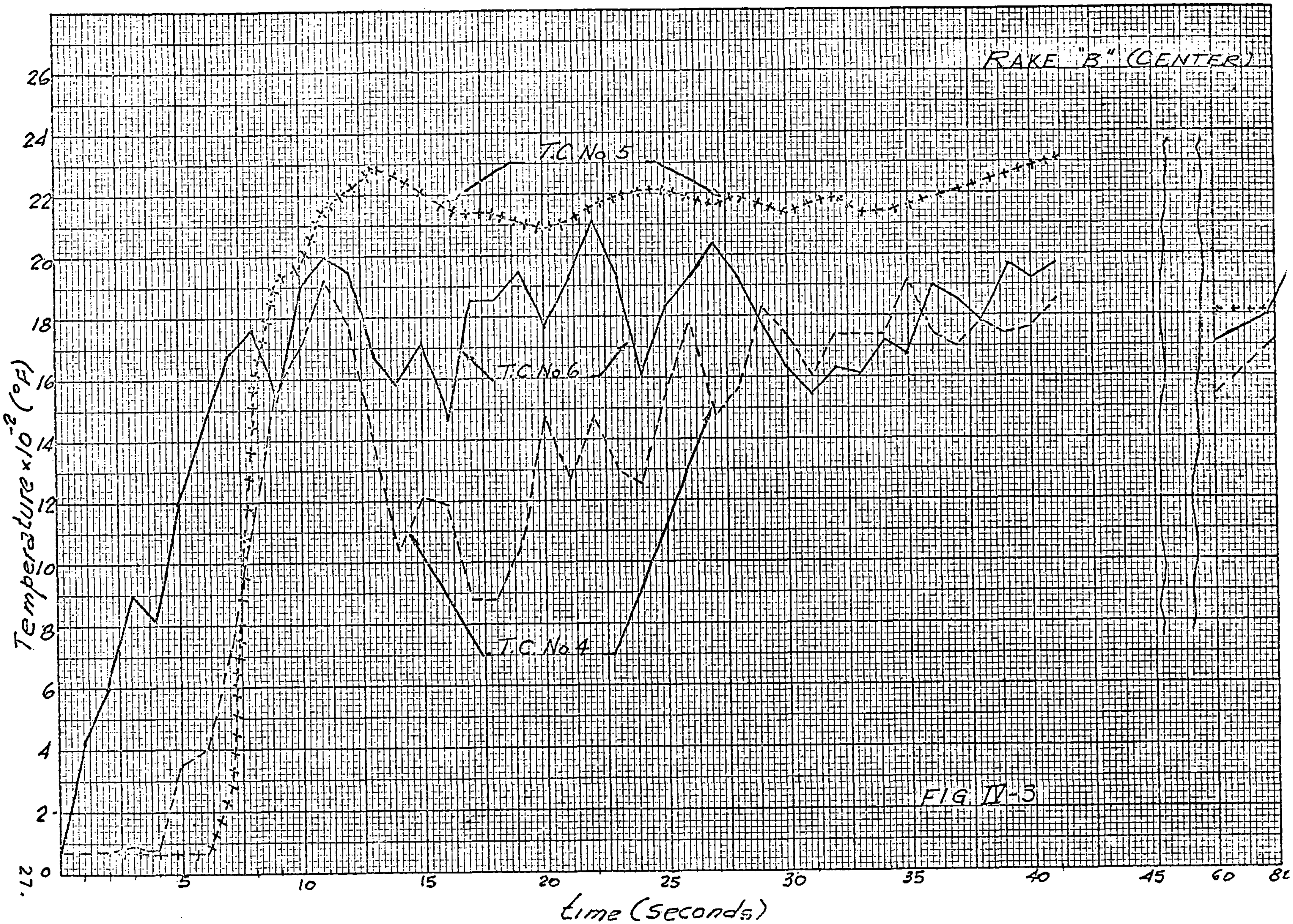

RAKE "B" (CENTER)
T.C. No 5
T.C. No 6
T.C. No 4
Temperature x10^{-2} (°F)
time (seconds)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
.27
5
10
15
20
25
30
35
40
45
60
80

FIG IV-5

V. IDENTIFICATION OF THE MAJOR FIRE CHARACTERISTICS AND FORMULATION OF THE ANALYTICAL FIRE MODEL.

The chemical and physical processes that determine the formation of a fire plume above a volatile pool of hydrocarbon aircraft fuel are characterized by the coupling of complex hydrodynamic, thermodynamic, chemical, heat and mass transfer mechanisms together with the geometry and extent of the pool and instantaneous atmospheric conditions. Fortunately, despite current incomplete understanding of fire processes which precludes an accurate description of the fire environment, detailed information concerning the chemical and physical mechanisms within the fire envelope is not required for a simulation of the actual fire environment. A reproduction of the actual environment, under controlled test facility conditions can be obtained once a few basic process parameters are formulated and operating conditions specified accordingly. The basic process parameters may be formulated on the basis of current fire research [12-16,27] including the full scale fire test described in Chapter IV.

The initial transient growth of the fire envelope begins with flame spread from the point of ignition. As the fire region above the pool thickens, large buoyancy forces together with increasing heat transfer rates to the fuel layer drive the fire plume higher as a result of the coupling between turbulent air-entrainment, fuel vaporization and decomposition and combustion. As discussed in Chapter III, after this initial growth period, the full fire plume persists for a period of time orders of magnitude greater than the intial transient period. Consequently, for the purposes of establishing simulation according to the postulated WCE, it is the "steady state," fully established plume condition that must be examined.

For the purpose of analysis, it is convenient to classify the turbulent fire column by three regions: [16]

A. The base region consisting of turbulent diffusion flames, strong buoyancy and high temperatures contributing to a dominance of radiant heat transfer.

B. An intermediate region in which radiation heat transfer remains important but chemical reaction is completed (and soot may begin to form).

C. An upper region which has cooled considerably and has a high density of soot.

It is the base region which is assumed to completely envelop a crash victim and it is this region that must be sufficiently understood to be duplicated under controlled FFSC conditions. Unfortunately, this region is by far the most difficult region to model and a suitable treatment of the competing physical and chemical processes cannot be found in the literature.

Nevertheless, it is essential that in order to insure a duplication of the thermo-chemical environment, sufficient understanding of the fire process must be obtained in order to determine the air/fuel ratio and overall temperature. These conditions cannot be <u>a priori</u> specified and must be established by an analysis of the real fire environment.

For the purposes of determining simulation feasibility, the major chemical, heat transfer and hydrodynamic characteristics of the fire will be identified and incorporated in a simple model. The model will be used to obtain the air/fuel ratio for the full scale fire test reported in Chapter IV, consistent with the measured temperature and reported fuel burning rates. [18,19] The model is then applied to the FFSC environment in order to specify thermal and air/fuel ratio operating characteristics.

As the fuel is vaporized, the hydrocarbon is introduced into the fire zone as a result of large heat transfer from the region above the fuel pool. The fuel, in this case JP-4, vaporizing at elevated temperatures, may enter into "cracking" reactions [26,28] or may be decomposed into carbon and hydrogen. These intermediate products diffuse into the reaction zone and since the fuel-air mixing process is limited by the turbulent entrainment characteristics of the fire plume, it is assumed that the hydrodynamic mixing and not chemical reaction rates control the combustion process. [27,30] The problem of carbon formation arises, since this diffusion region must have a low oxygen concentration and as long as the temperature is high enough to decompose the fuel, unreacted free carbon may be present. As a result of an overall oxygen deficiency throughout the plume, this carbon may never enter into further reaction and will ultimately form soot in the colder regions of the plume. If the carbon manages to enter regions which contain H_2O , there is a tendency for the carbon to react to form CO .

At this point a reasonable judgment must be made regarding the components present in the product gases. Since experimental measurements of fire gas composition are difficult if not impossible to obtain, assumptions must be made on the basis of thermodynamic considerations. The anticipated oxygen deficiency leads one to suspect that the product gases will be composed mainly of CO , H_2O , H_2 , N_2 and CO_2 . While some traces of OH , H , O and oxides of Nitrogen may be present, the chemical equilibrium constants for the reactions

$$H_2O \rightleftharpoons \tfrac{1}{2} H_2 + OH$$

$$\tfrac{1}{2} O_2 \rightleftharpoons O$$

$$\tfrac{1}{2} N_2 + \tfrac{1}{2} O_2 \rightleftharpoons NO$$

$$\tfrac{1}{2} H_2 \rightleftharpoons H$$

are of the order 10^{-6} except for the nitrogen reaction which is of the order 10^{-3} .

Since the equilibrium constant is proportional to $\left(\frac{\text{products composition}}{\text{reactants composition}}\right)$, at 1 atmosphere, it may be assumed with reasonable assurance that H_2O , O_2 and H_2 are stable as far as these dissociation reactions are concerned and OH , O , H should not be anticipated in sizeable amounts. While the equilibrium constant of 1.92×10^{-3} for the nitrogen reaction is small. further evidence of the absence of NO is the slow rate with which this reaction proceeds, [27] suggesting that even the low concentrations predicted by equilibrium considerations may not be attained. This observation concerning the relationship between size of an equilibrium constant and the associated reaction rate becomes important in the selection of products of combustion for the reactions between H_2, H_2O, C and O_2. All of these reactions compete for the deficient oxygen and are associated with large equilibrium constants, yet there is no _a priori_ thermodynamic reason to associate a large equilibrium constant with reaction rate. However, it is customary to assume that in such turbulent fire plumes the hydrodynamics of the air entrainment process is a stronger limitation than reaction rates and the equilibrium constant should therefore provide a good indication of component composition. On this basis, for the reactions listed below* with the relative size of their equilibrium constants (for the suggested fire temperature of 2100°F), an _a priori_ estimate of the relative component composition results in a large portion of CO and H_2, substantial H_2O with somewhat less CO_2. Since the N_2 is assumed not to enter into reaction, its concentration by mass is unchanged.

A major difficulty concerns the treatment of carbon whose presence is first revealed by the intense luminosity of the flame and later by considerable sooting. Although the presence of free carbon cannot be overlooked, difficulties in computing realistic

---

*(1) $H_2O + \frac{1}{2} C \rightleftharpoons CO + H_2, 10^3$; (4) $H_2O + \frac{1}{2} C \rightleftharpoons \frac{1}{2} O_2 + H_2, 10$
(2) $CO + \frac{1}{2} O_2 \rightleftharpoons CO_2, 10^5$; (5) $C + CO_2 \rightleftharpoons 2CO, 10^3$
(3) $C + \frac{1}{2} O_2 \rightleftharpoons CO, 10^9$; (6) $H_2 + \frac{1}{2} O_2 \rightleftharpoons H_2O, 10^6$

concentrations were experienced in preliminary computations. Since little more information concerning equilibrium carbon calculations could be found other than cautions to the effect that it is a difficult and rarely attempted problem, calculations are performed without free carbon and its presence is determined a posteriori. [27]

Assuming the products are composed mainly of N_2 , CO , H_2O , CO_2 and H_2 , a chemical model is posulated consistent with the air deficient situation. As the fuel is entrained into the fire region, it is assumed that all of the carbon is oxidized to CO , the remaining O_2 oxidizes sufficient H_2 to H_2O and excess H_2 is liberated. It is therefore implicitly assumed that the carbon has a large tendency to form CO (reaction 3, page 32). The initial components (reactants) may therefore be obtained once the C/H composition of the fuel is known.

Using JP-4 fuel data,[34,35] an equivalent hydrocarbon molecule may be obtained in the form

$$C_{9.64}\,H_{2(9.50)}$$

The assumed oxidation process results in

$$C_{9.64}\,H_{2(9.50)} + PO_2 \rightleftharpoons 9.64\,CO + (9.50+9.64-2P)\,H_2 + (2P-9.64)H_2O$$

where the O/C ratio is given by $\frac{2P}{9.64}$ and the intial oxygen mole number P is unknown.

The reactants are immediately determined to be (per mole of JP-4)

$$9.64\ CO$$

$$(9.50 + 9.64 - 2P)\ H_2$$

$$(2P - 9.64)\ H_2O$$

The reaction below involving H_2, CO_2, CO, H_2O is then assumed to determine the equilibrium concentrations of these components at the fire temperature of 2100°F.

$$H_2 + CO_2 \rightleftharpoons CO + H_2O$$

$$k(2100^{\circ}F) \equiv \frac{(N\ CO)(N\ H_2O)}{(N\ H_2)(N\ CO_2)}$$

Since a stoichiometric O/C for JP-4 is 2.98 and sooting may be expected for $O/C \sim 1$, fire operation should require $1 < O/C < 2.98$. This will be used as a criterion for estimating a range of P oxygen moles in the thermo-chemical fire analysis given in Chapter VI.

At the conclusion of the fire analysis, the possibility of sooting is considered by an examination of the equilibrium composition between the components CO, CO_2 and C. For these components, one has the Boudouard reaction, [27]

$$2\ CO \rightleftharpoons CO_2 + C$$

with an equilibrium constant at 1 atmosphere of

$$k_B \equiv \frac{(N\ CO)^2}{(N\ CO_2)}$$

where $N\ CO$ and $N\ CO_2$ are the number of moles of CO and CO_2 (for the fire temperature of 2100°F, $k \sim 628$)

IF the actual concentration $\frac{(N\ CO)^2}{N\ CO_2}$ is computed to be greater than k_B, sooting can be expected.

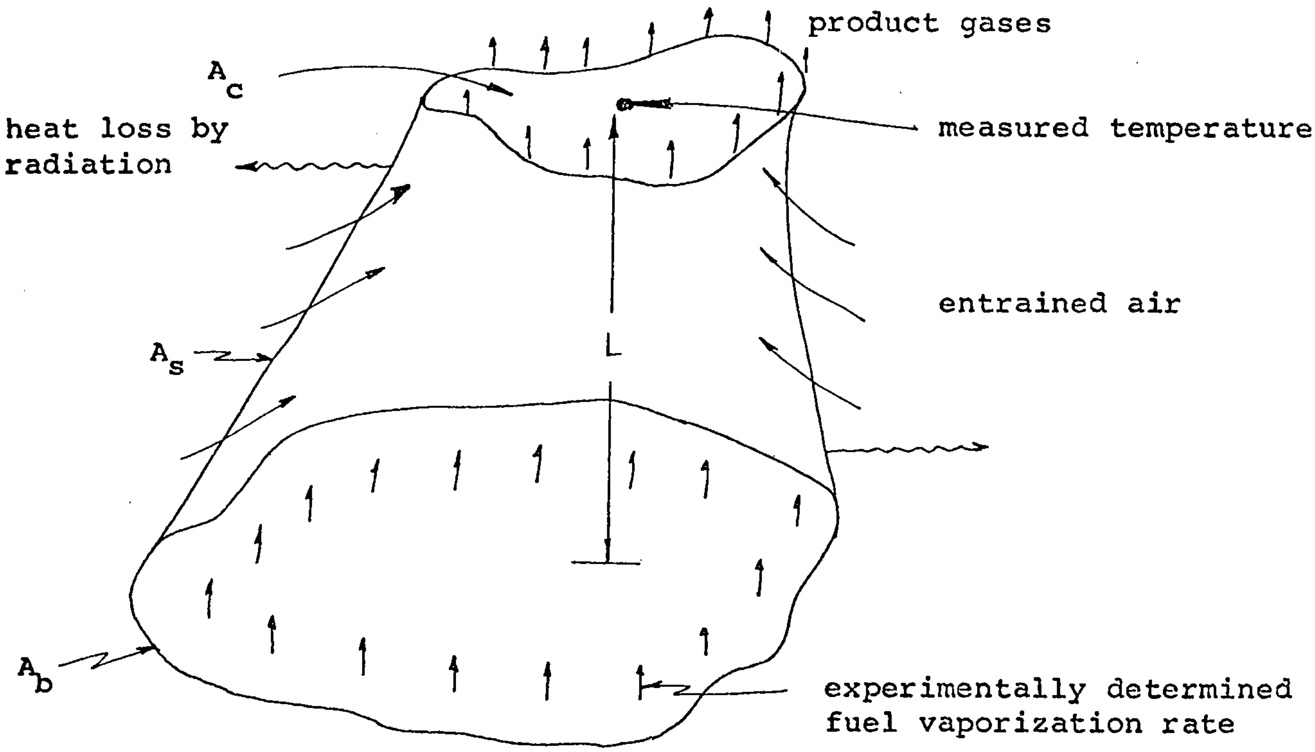
VI. THERMO-CHEMICAL ANALYSIS OF THE JP-4 FUEL FIRE AND SPECIFICATION OF THE FACILITY OPERATING CONDITIONS.

In the usual industrial furnace application, complete combustion with minimum excess air is desired. Contrary to usual design practice, however, the fire simulation facility must run fuel rich. The purpose of the analysis that follows is to ascertain the air/fuel ratio required to match fire plume conditions at the measured fire temperature.

The air/fuel ratio obtained from the actual fire is then used to determine the volume flow rate of air required by the FFSC. In addition, a thermal analysis of the facility at this specified air/fuel ratio provides necessary information to establish overall facility cooling requirements.

According to the thermodynamic description of a system of reacting components, the equilibrium concentration is solely a function of temperature and atomic concentrations. The analysis therefore must determine the O/C ratio which is consistent with conservation of energy and hydrodynamic air entrainment in the real fire situation. Although it is not feasible to account for all of the actual reactions involving all possible components, those components contributing a major portion of the system energy are included. Since all of the carbon is assumed to enter into reaction, the computed oxygen requirement may be high. However, this may be balanced by incomplete turbulent mixing in the FFSC.

Conservation of energy for the actual fire envelope shown below is given by



$$Q_{Fire\text{-}air} + Q_{Fire\ ground} = \dot{m}\left\{\sum_{j=1}^{4} N_j\,(h_j + H_j^f) + 3.76\,N_{O_2}^o\,(h_{N_2} - h_{N_2}(T_a)) - N_{O_2}^o\,h_{O_2}(T_a) - (h_{fuel} + H_{fuel}^f)\right\} \quad \text{(VI-1)}$$

$j = 1,2,3,4$ corresponds to components CO, CO_2, H_2O, H_2

and $h_j \equiv h_j(2100^o) - h_j(77^oF)$, component enthalpy $\left(\frac{BTU}{lb\ mole}\right)$

$H_j^f \equiv$ heat of formation of component j.

$N_{O_2}^o \equiv$ initial oxygen mole number requirement per mole of fuel

$N_j \equiv$ moles of component j per mole of fuel

$T_a \equiv$ ambient temperature

N_{N_2}	nitrogen mole number requirement
$\dot{m}$	moles of fuel vaporized per second
$Q_{Fire-air}$	heat loss from fire to ambient air
$Q_{Fire-ground}$	heat loss from fire region to ground
A_s	lateral fire envelope surface area
A_b	pool base area
A_c	fire plume cross-section area at height L

For the purposes of obtaining an equilibrium composition between H_2, H_2O, CO_2, CO and inert N_2, a set of initial reactants are obtained from JP-4 according to the following oxidation equation (VI-2), discussed in Chapter V.

$$C_{9.645}\,H_{2(9.5004)} + PO_2 \rightleftharpoons 9.645\ CO + (2\cdot P - 9.645)\ H_2O + (9.5004 + 9.645 - 2.P)\ H_2 \qquad \text{(VI-2)}$$

where P moles O_2/mole fuel is to be determined.

Since air entrainment and intrafire mixing are assumed to control the combustion process, the concentrations of CO, CO_2, H_2O and H_2 are given by their equilibrium composition for the reaction

$$H_2 + CO_2 \rightleftharpoons CO + H_2O \qquad \text{(VI-3)}$$

which has equilibrium constant $k(T)$,

$$k(T) = \frac{(N_{N_2O})(N_{CO})}{(N_{H_2})(N_{CO_2})} \qquad \text{(VI-4)}$$

At 2100° , $k(T) = 2.1532$ [30,32] $k(T)$ is related to the mole numbers by the equilibrium requirement given by equation (VI-4).

Reaction (1) can be written in the form [33]

$$\sum_{j=1}^{4} \nu_j A_j$$ where A_j are the molecular components

H_2, CO_2 , CO or H_2O and ν_j are the corresponding stoichiometric coefficients (negative for the reactants) in equation (VI-3).

If the initial moles of each component entering into reaction is N_j^o , $j = 1,2,3,4,$ the final number of moles of each component in the equilibrium composition is given by

$$N_j = N_j^o - \nu_j \, \Delta N \quad , \quad J = 1,2,3,4 \qquad \text{(VI-5)}$$

where ΔN is a proportionality factor for the mole ratios δN_j entering into reaction,

$$\delta N_{H_2} : \delta N_{CO_2} : \delta N_{CO} : \delta H_2O = -1 : -1 : +1 : +1$$

The equilibrium composition requires that equations (VI-5) satisfy equation (VI-4) and one obtains the following equation for ΔN

$$k(T) = \frac{(N^o_{H_2O} + \Delta N)(N^o_{CO} + \Delta N)}{(N^o_{H_2} - \Delta N)(N^o_{CO_2} - \Delta N)} \qquad \text{(VI-4')}$$

Equations (VI-1), (VI-4') and (VI-5) must be solved simultaneously with property data given below consistent with the constraint that the required O_2 mole rate P can be supplied by a turbulent entrainment mechanism. A semi-empirical entrainment model for strongly buoyant plumes [16] which relates vertical fire velocity to the air entrainment rate using an empirical constant (.17) is given by equation (VI-6).

TABLE VI-1

Property Data

	Mole wt., M	Enthalpy h(2100)-h(77) BTU/lb mole	Heat of formation at 77°F H^f $\frac{BTU}{lb\ mole}$
CO	28.011	15,530	- 47,551
H_2O	18.016	19,136	- 104,036
H_2	2.016	14,524	0
CO_2	44.011	24,052	- 169,297
N_2	28.011	15,355	0
JP-4	135		- 137,253

$$m_{air} = (.17)(\rho_{air}\,\rho_P)^{\frac{1}{2}} \quad A_s \, V_P \qquad \text{(VI-6)}$$

where ρ_P and V_P are the density and vertical velocity of the plume gases. ρ_P and V_P are determined as follows:

An average gas molecular weight is given by

$$M_{ave} = \sum_{j=1}^{5} \frac{N_j}{N_T} M_j \,,$$ in this case the summation includes the inert nitrogen.

M_j is the molecular weight of component j, N_j the moles of component j and $N_T = \sum_{j=1}^{5} N_j$.

An average gas constant is given by

$$R_{ave} = \frac{\bar{R}}{M_{ave}} = \frac{1545.33}{M_{ave}}$$

where $\bar{R}$ is the universal gas constant. ρ_P is then obtained from the ideal gas equation of state

$$\rho_P = \frac{\text{pressure}}{R_{ave}\ T} = \frac{14.7 \times 144}{R_{ave}\ 2560^{\circ}R}$$

The vertical gas velocity is determined by the flux of mass at plume cross-section L.

$$V_P = \frac{\dot{m}}{\rho_P A_c}$$

where $\dot{m}\ \frac{\text{lbm gas}}{\text{sec}} = \dot{m}\ \frac{\text{moles fuel}}{\text{sec}}\ 4.76\ N_{O_2} \times \frac{M_{O_2}}{M_{air}}$

A solution for P is determined once (VI-4), (VI-4'), (VI-5) and (VI-6) are simultaneously satisfied. Results for O/C ratios from 1.25 to 2.40 are presented in figures VI-1, VI-2 and VI-3. It should be noted that the stoichiometric O/C ratio is 2.98.

Referring to fig. VI-1, it is observed that the chemistry and energy requirements are satisfied simultaneously for an O/C ratio of approximately 1.7. It is also to be noted that this

O/C ratio is realistic in terms of the turbulent air entrainment mechanism, as can be seen by examination of fig. VI-2.

According to the carbon deposition discussion in Chapter V, an examination of the CO , CO_2 concentration in the form $(N_{CO})^2/(N_{CO_2})$ will determine the tendency to form soot.

The O/C ratio of 1.7 corresponds to an equilibrium constant of 15 for the reaction $C + CO_2 \rightleftharpoons 2CO$. This equilibrium constant requires a composition $(N_{CO})^2/N_{CO_2}$ of 1 at 1427°F, indicating that flame cooling by wind gusts in the intermediate plume region will result in considerable sooting as soon as the plume temperature falls below 1427°F, despite the initial assumption that all of the carbon enters into reaction.

The required FFSC volumetric air flow rate corresponding to a given O/C ratio may now be computed.

$$\text{Air flow rate} = \left(\frac{O}{C}\right) \times \left(\frac{9.645 \text{ N atoms C/mole JP-4}}{2 \text{ N atoms O/mole } O_2}\right) \times$$

$$(4.76 \text{ moles air/mole } O_2) \times (.004362 \text{ moles fuel/min-ft}^2)$$

$$\times \left(387 \frac{\text{SCF}}{\text{mole air}}\right) \times \left(\frac{96 \text{ ft}^2}{60 \text{ sec/min}}\right) = (62 \text{ O/C}) \text{ SCF/sec.}$$

In this equation N is Avogadro's number, SCF means Standard Cubic Feet and an area of 96 ft^2 corresponds to the base area of the FFSC described in Chapter VIII. This result is presented in fig. VI-4.

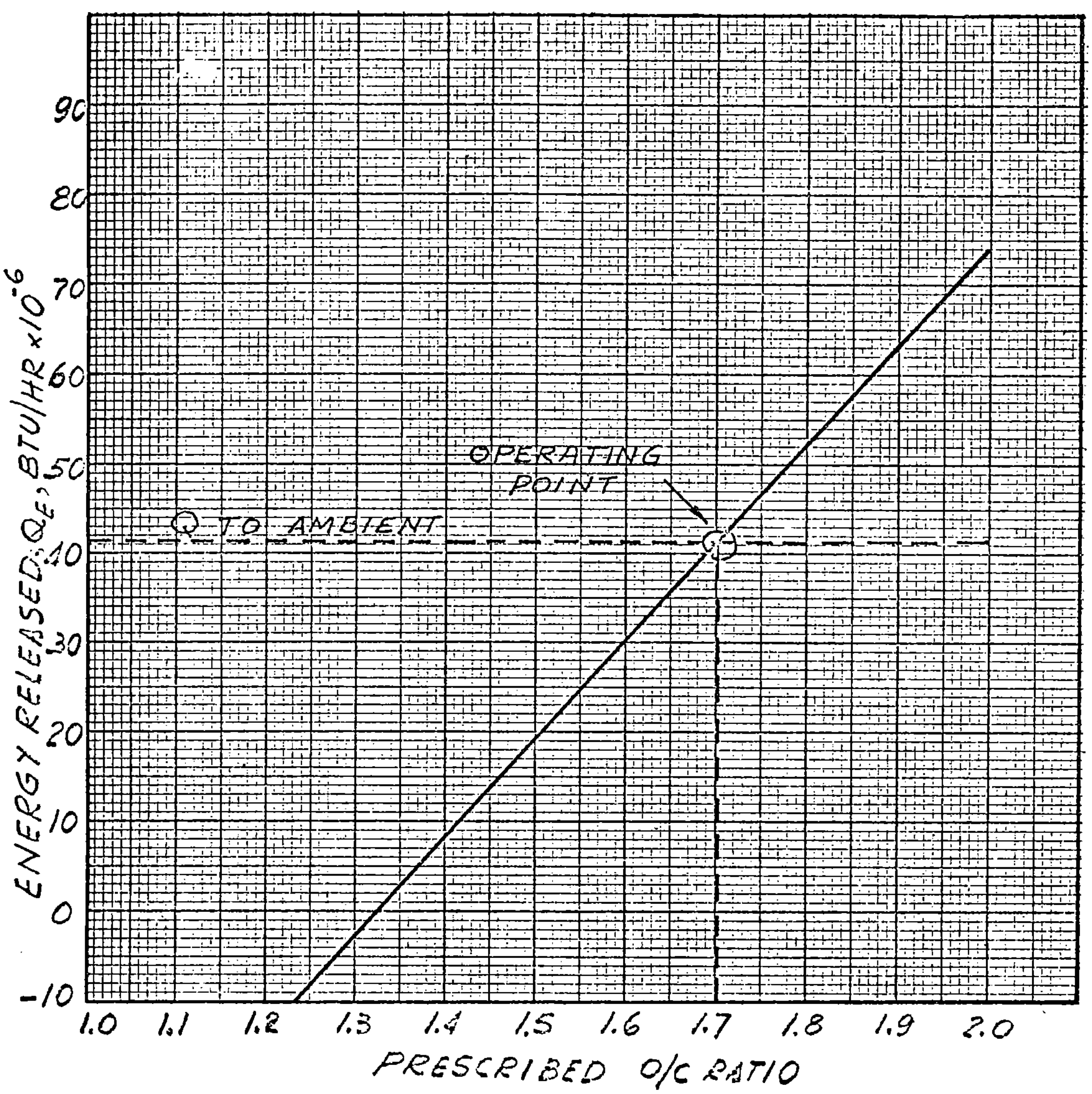


Figure VI-1. Determination of Air-Fuel Ratio Characteristics of a JP-4 Turbulent Fire Plume

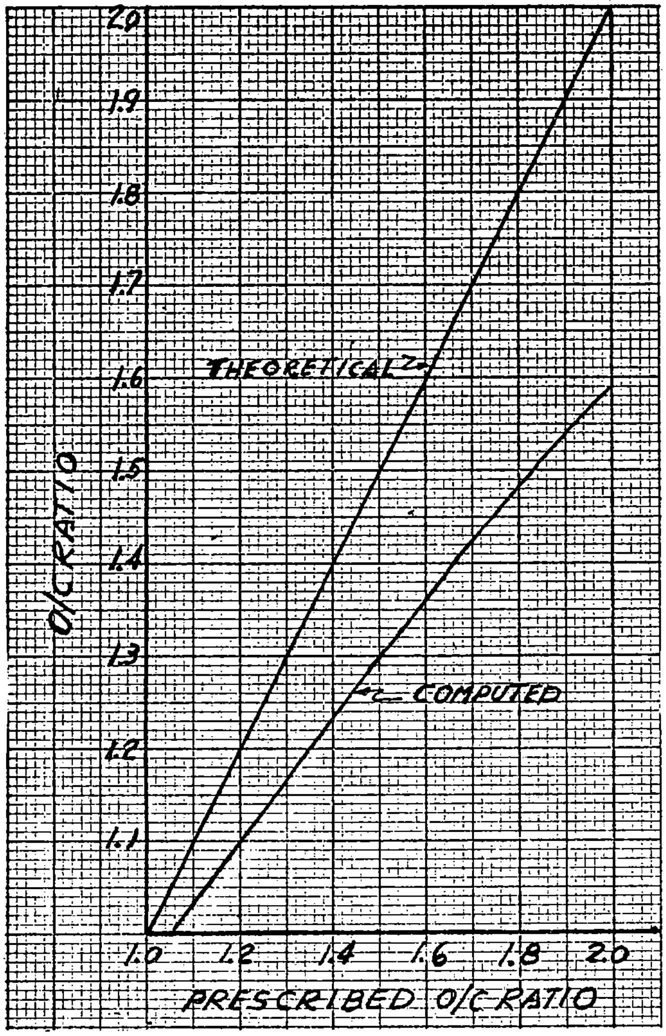


Figure VI-2. Comparison of the Turbulent Air Entrainment Characteristics of the Fire Plume with the Combustion Requirements

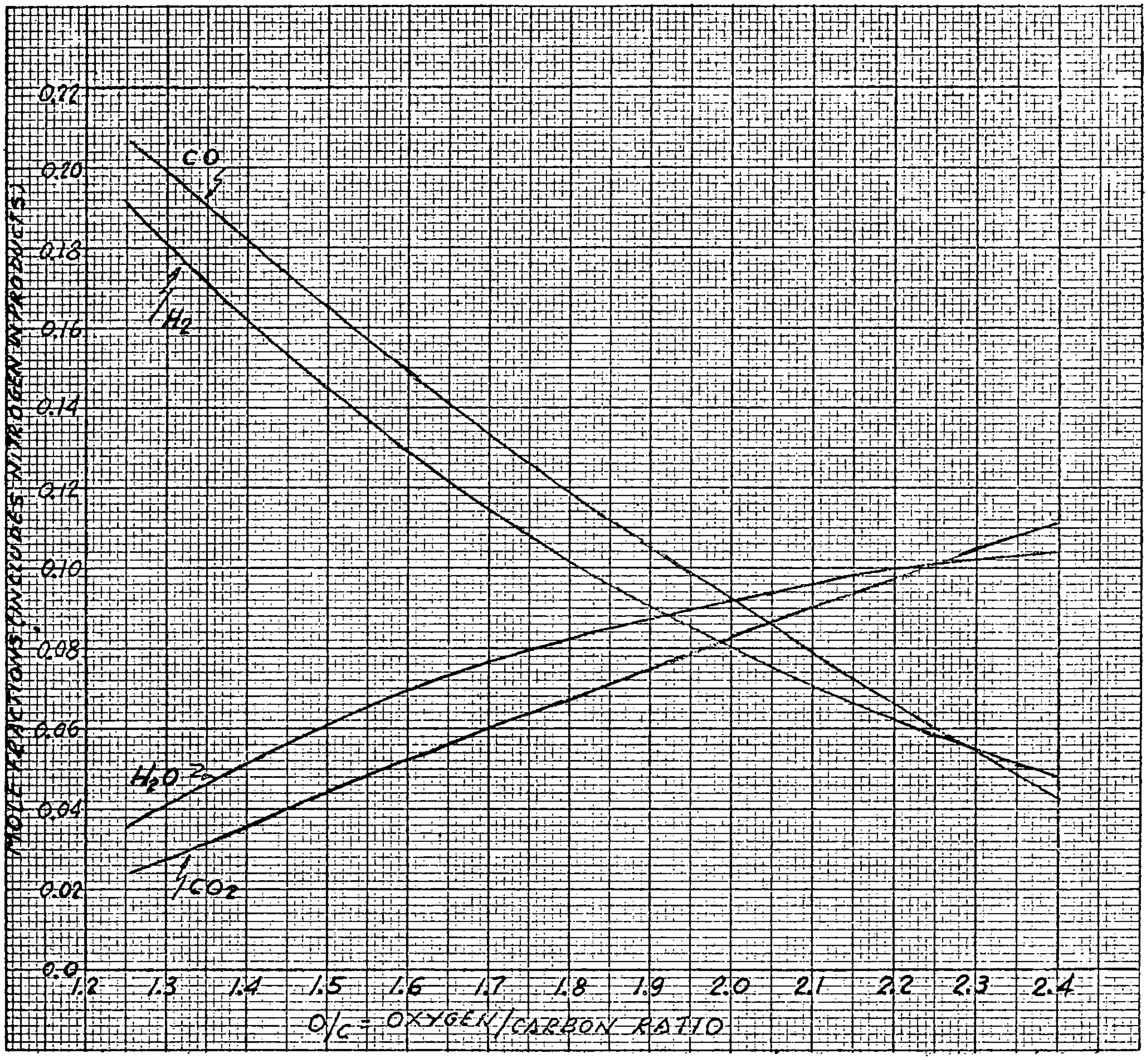


Figure VI-3. Concentration of Dominant Fire Environment Gas Components

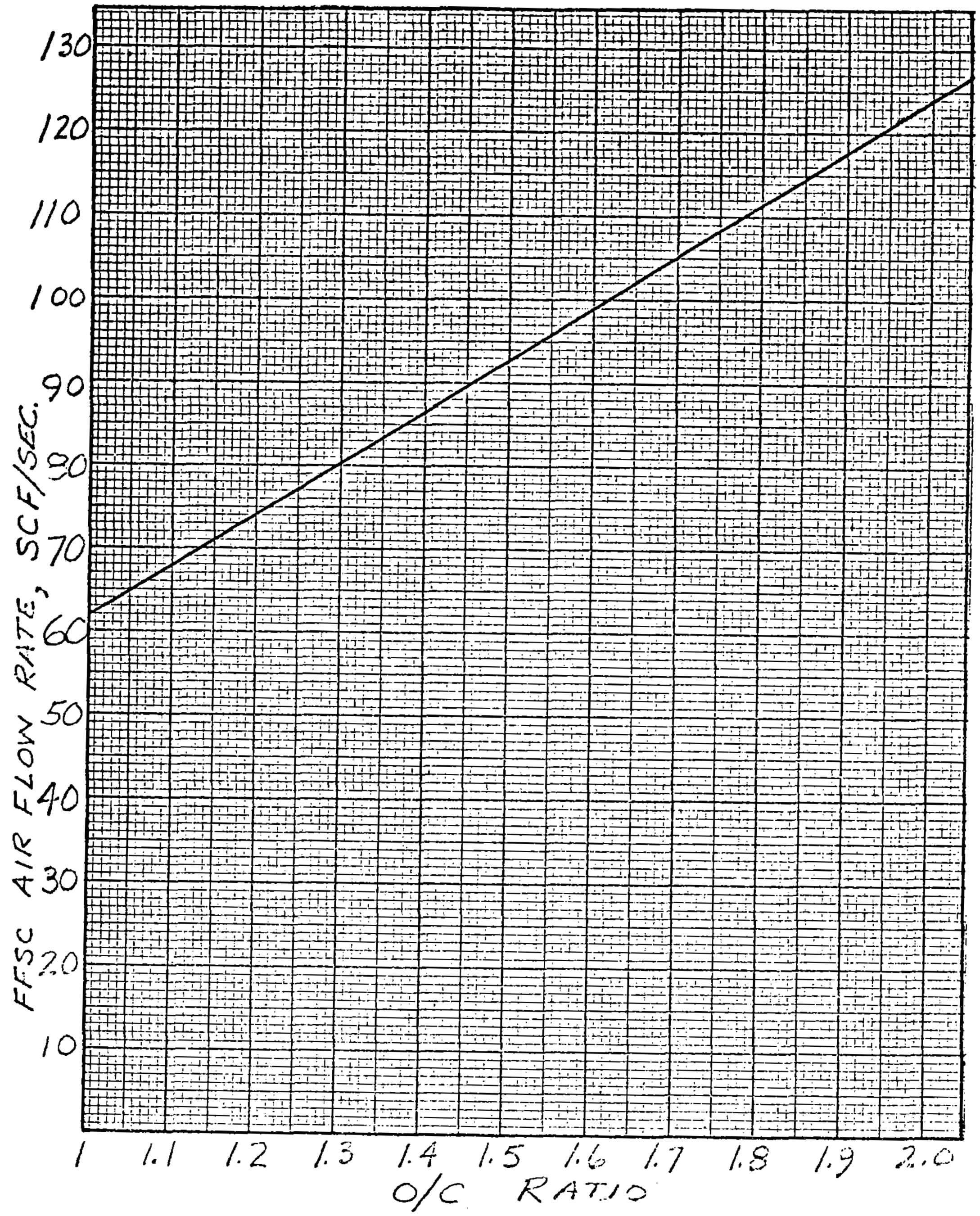


Figure VI-4. FFSC Air Requirement as Function of O/C Ratio

VII. WALL HEATING REQUIREMENTS

As reported in Chapter IV and discussed in Chapter V, a large pool fire is characterized by negligibly small transverse temperature gradients, except possibly near the periphery. Since it is the WCE which is to be simulated in the FFSC, it must therefore be the objective of the facility design to simulate the core region of the field fire, i.e., transverse temperature gradients should not exist in the FFSC. Therefore, the WCE can conceptually be identified with the "local environment" of fig. VII-1. Several physical differences between the "local environment" of fig. VII-1 and the FFSC fire are immediately evident.

In the field fire, mass transfer takes place between the local environment and the remainder of the fire. In this manner oxygen is supplied to the local environment to support combustion. Clearly, the presence of a solid wall completely surrounding the local environment would starve the fire in this region. In the preceding chapters, the air requirements of the local environment corresponding to the WCE were established and in the proposed FFSC design provision is made for supplying this oxygen.

Even if the proper amount of air theoretically required to establish the WCE in the FFSC were supplied, the thermal influence of the walls could result in failure to actually establish the WCE. There are two important reasons for this.

If the FFSC walls are at a lower temperature (T_w) than the fire (T_F) there will be a radiant and convective heat exchange between the fire and the walls which does not correspond to the magnitude of the heat exchange between the local environment and the remainder of the fire in fig. VII-1. The effect of this would be to lower the fire temperature compared to the WCE unless the air injection were changed to compensate for this. However, this procedure would alter the fire chemistry and is therefore considered unacceptable.

From the viewpoint of the manikin, cold walls represent a radiant sink which is not present in the large field fire. In fig. VII-1, radiant energy incident on the manikin (test specimen) originating from <u>beyond</u> the local environment is characterized by the black body monochromatic intensity corresponding to the fire temperature, $I_{b\nu}(T_F)$. The radiation incident on the manikin is [23]

$$I_\nu = I_{b\nu}(T_F)\, e^{-\kappa_\nu \ell} + \int_0^\ell \kappa_\nu\, I_{b\nu}\, e^{-\kappa_\nu S}\, dS \tag{VII-1}$$

which integrates to

$$I_\nu = I_{b\nu}(T_F) \qquad \text{(Field Fire)} \tag{VII-2}$$

For the FFSC

$$I_\nu = I_{w\nu}\, e^{-\kappa_\nu \ell} + \int_0^\ell \kappa_\nu\, I_{b\nu}\, e^{-\kappa_\nu S}\, dS \tag{VII-3}$$

which integrates to

$$I_\nu = I_{w\nu}\, e^{-\kappa_\nu \ell} + I_{b\nu}(T_F)\,[1-e^{-\kappa_\nu \ell}] \qquad \text{(FFSC)} \tag{VII-4}$$

Clearly, the incident radiation on the manikin will have the same strength and spectral distribution in the field fire, eq. (VII-2), and in the FFSC, eq. (VII-4), only if

$$I_{w\nu}\, e^{-\kappa_\nu \ell} = I_{b\nu}(T_F)\, e^{-\kappa_\nu \ell} \tag{VII-5}$$

Equation (VII-5) can be satisfied in one of two ways or a combination of both. If the FFSC walls are blackened (which, in any event, probably cannot be avoided, since there is a large amount of carbon in the fire) and maintained near a temperature equal to the fire temperature, then $I_{w\nu} = I_{b\nu}(T_F)$ and eq. (VII-5) will be satisfied. Alternately or concurrently, if ℓ is large enough, both sides of eq. (VII-5) will approach zero which implies that I_ν in eqs. (VII-2) and (VII-4) will be the same. As mentioned in Chapters III and IV, 95% or more of the incident radiation comes for a distance of approximately three feet from the receiving surface. In other words, for $\ell \approx 3$ ft, $e^{-K_\nu \ell} \approx .05$ and I_ν from eq. (VII-4) will be approximately equal to $I_{b\nu}(T_F)$.

However, due to the uncertainty in the 3 ft. figure quoted above, it was decided to analyze the transient response of the furnace walls, i.e., to estimate the time required to achieve a wall surface temperature near 2100°F if they are initially cold and the fire temperature is nominally 2100°F. In order to perform this analysis, either the heat flux to the wall from the fire or the effective heat transfer coefficient between the two is needed. The total heat flux to the wall is the sum of the radiant and convective heat flux, i.e.,

$$Q_T = Q_R + Q_C \tag{VII-6}$$

Since the width of the FFSC will be on the order of 8 feet, the fire will be radiatively "black" with respect to the walls. Then, for black walls,

$$Q_T = \sigma(T_F^4 - T_w^4) + h_c(T_F - T_w) \qquad \text{(VII-7)}$$

where σ is the Stefan-Boltzmann constant and the temperatures are measured on an absolute scale. Q_T as a function of T_w is plotted in fig. VII-2. An effective heat transfer coefficient is defined as

$$h = Q_T/(T_F - T_w) \qquad \text{(VII-8)}$$

and is also shown in fig. VII-2. It is clear from fig. VII-2 that the concept of an average Q_T or h , applicable during the entire wall transient period, will probably not lead to accurate results. This is now demonstrated.

Treating the furnace wall as semi-infinite, Carslaw and Jaeger[24] give the solution for the wall <u>surface</u> temperature as

$$T_w(t) = T_i + \frac{2\bar{Q}}{k}\left(\frac{\alpha t}{\pi}\right)^{\frac{1}{2}} \qquad \text{(VII-9)}$$

when $\bar{Q}$ is constant for the entire heating process.

For an initial temperature, T_i , of $100^{\circ}F$ and using representative fire-brick property data[25], the time required to achieve $T_w = 2000^{\circ}F$ is plotted against heat flux in fig. VII-3. For the range of heat fluxes in fig. VII-2, the required heating time would range from ½ minute to ½ hour. This range is too large to be useful for predicting actual behavior. A more meaningful analysis therefore had to be undertaken. Since Q_T depends on T_w and T_w depends on time, t, (in an *a priori* unknown manner) Q_T can be treated as a function of time. Again Carslaw and Jaeger[24] present the solution, which is,

$$T_w(t) = T_i + \frac{1}{k}\left(\frac{\alpha}{\pi}\right)^{\frac{1}{2}} \int_0^t \frac{Q_T(t-\tau)}{\sqrt{\tau}}\, d\tau \qquad \text{(VII-10)}$$

A more reasonable, but conservative, estimate of the FFSC wall surface temperature response is then obtained by replacing the actual Q_T in fig. VII-2 by the dashed line in fig. VII-2. Since Q_T is thereby underestimated at all times, the solution will be conservative. Equation (VII-10) then becomes, after integration,*

$$T_w(t) = T_i + \frac{2}{k}\left(\frac{\alpha}{\pi}\right)^{\frac{1}{2}} \Big\{ Q_1\sqrt{t_1} + Q_2(\sqrt{t_2}-\sqrt{t_1}) + Q_3(\sqrt{t_3}-\sqrt{t_2})$$

$$+ Q_4(\sqrt{t} - \sqrt{t_3})\Big\} \quad , \; t \geq t_3 \qquad \text{(VII-11)}$$

Q_1, Q_2, Q_3 and Q_4 were taken as $4\text{x}10^4$, $3\text{x}10^4$, $2\text{x}10^4$ and $1\text{x}10^4$ BTU/hr-ft^2 (see fig. VII-2). The times t_1, t_2 and t_3 corresponding to the time required to reach the wall temperatures corresponding to Q_1, Q_2, etc., i.e., 1700°F, 1820°F and 1920°F are not known *a priori* and an iterative scheme for determining

* For $t<t_i$, $i = 1,2,3$ the appropriate terms in (VII-11) were deleted.

$T_w(t)$ was therefore required. The results, showing $T_w(t)$ as well as t_1, t_2 and t_3, are presented in fig. VII-4. Though these results are believed to represent a reasonable transient response of the <u>surface</u> temperature of a fire-brick wall, it is <u>not</u> to be inferred that the <u>entire</u> wall has reached a steady state temperature distribution in 2½ minutes. This could take hours.[25] However, insofar as satisfying the requirement that the wall radiate to the manikin as a black body at approximately the fire temperature, this result is believed to be reasonable.

An alternate passive wall scheme which was analyzed, consists of a thin metal facing or stand-off between the fire brick and the fire. Because of the large effective convection heat transfer coefficient between a surface and the flames (see fig. VII-2), the metal will have a virtually uniform temperature.* The solution to this problem[25] is

$$T_w(t) = T_F - (T_F - T_i)\, e^{-\frac{h\alpha}{kS} t} \qquad \text{(VII-12)}$$

where S is the plate thickness. Since h as well as the thermal properties of the plate depend on T_w, eq. (VII-12) was applied over discrete temperature intervals. For each interval average values of h, α and k were used and T_i, the initial tempera-

* The Biot number[25] will be on the order of 10^{-3} for a 1/16 inch steel plate, implying negligibly small temperature gradients in the plate.

ture for the interval was taken as the final wall temperature for the preceding interval. In this manner the time required for each increment in wall temperature (200°F) was established. The resulting transient response of a 1/16" plate is shown in fig. VII-5. The small additional improvement in transient response afforded by a metal wall does not appear to warrant the additional constructional complexities implied by such an arrangement.

In addition to providing the proper radiant background, the walls must also be capable of passing the heat liberated by the fire if the fire temperature is to be kept from going beyond the temperature of the WCE. For an O/C ratio on the order of 1.7 (see Chapter VI), the rate at which heat must be removed from a fire in the proposed FFSC (see Chapter VIII) having a base area of 96 ft^2 and a wall surface area (including ends) of 320 ft^2 is

$$Q_{\substack{\text{Removal}\\ \text{rate}}} = \frac{41.275 \times 10^6}{320} \times \frac{96}{540} = 2.3 \times 10^4 \ \text{BTU/hr-ft}^2 \qquad \text{(VII-13)}$$

The heat removing capability of a fire-brick wall with a surface temperature of 2000°F which is initially at 100°F varies with time according to the relation [25]

$$Q = \frac{k}{\sqrt{\pi \alpha}} \frac{(T_w - T_i)}{\sqrt{t}} \approx \frac{.463 \times 10^4}{\sqrt{t}} \ \text{BTU/hr-ft}^2 \qquad \text{(VII-14)}$$

At 5 minutes and 1 hour, this corresponds to 1.6 and 0.4×10^4 BTU/hr-ft^2 respectively, which is less than the required rate. It can therefore be concluded that additional cooling of the walls may be necessary. Conceivably, this could be accomplished by inserting water cooling pipes or channels in the FFSC walls. The required total water flow rate would be between 50 and 100 GPM, which is feasible. The precise definition of the cooling requirements must be considered as part of the detailed engineering design.

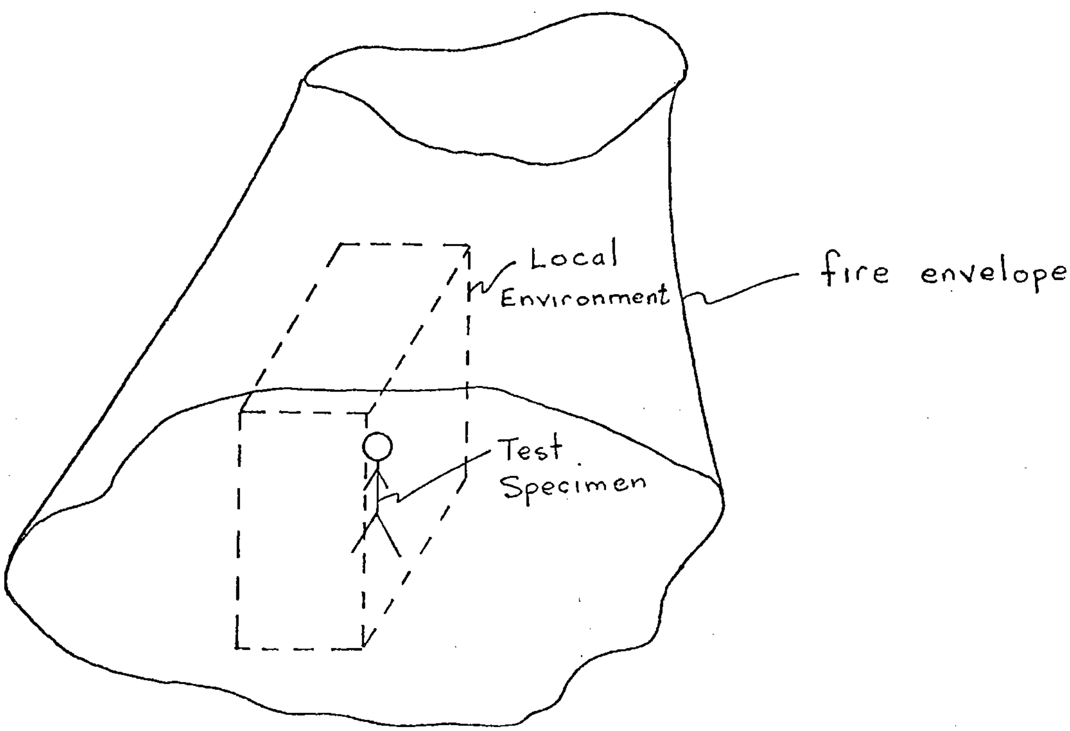


Figure VII-1. Local Environment in a Large Pool Fire

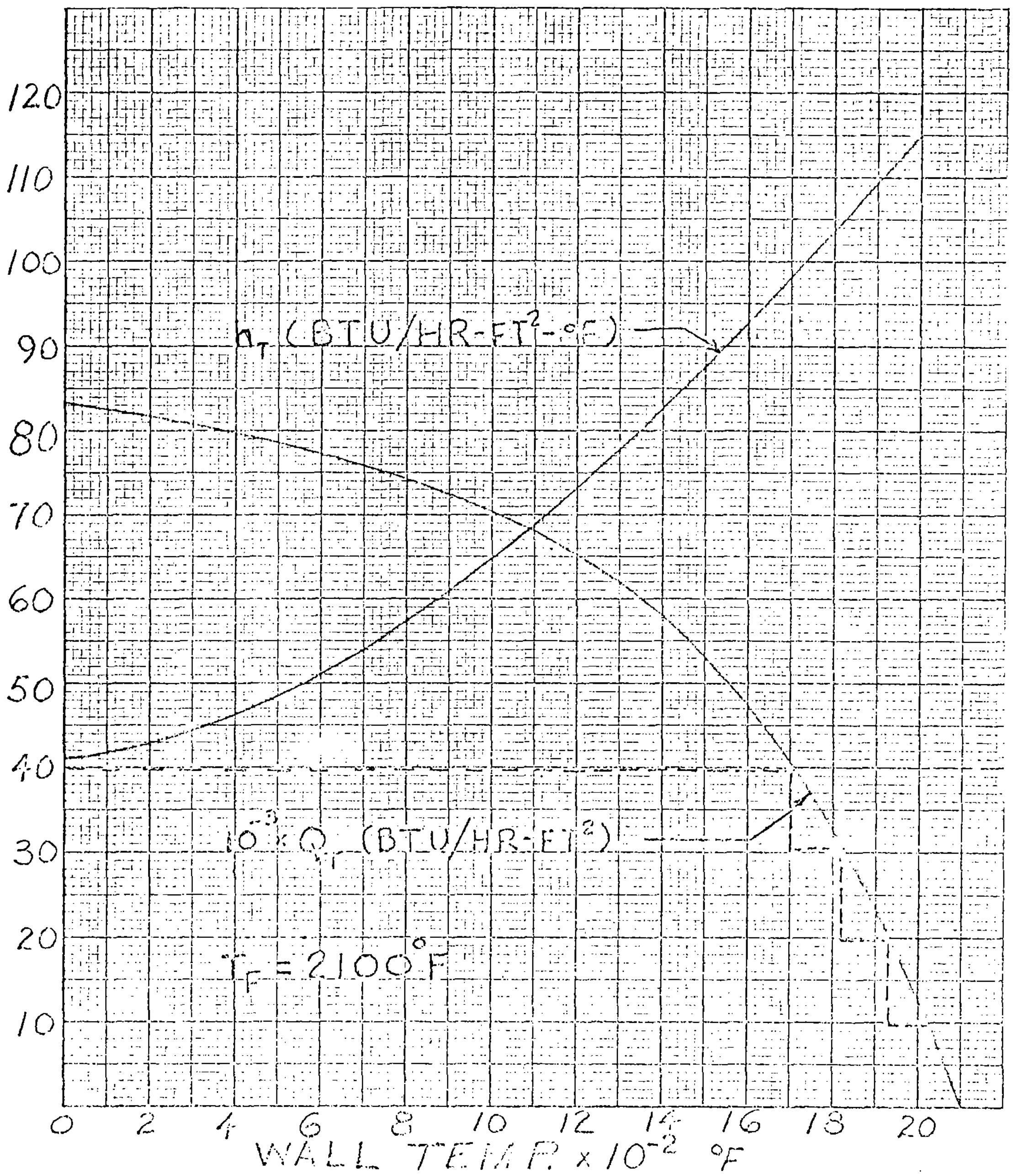


Figure VII-2. Total Wall Heat Flux vs. Wall Surface Temperature

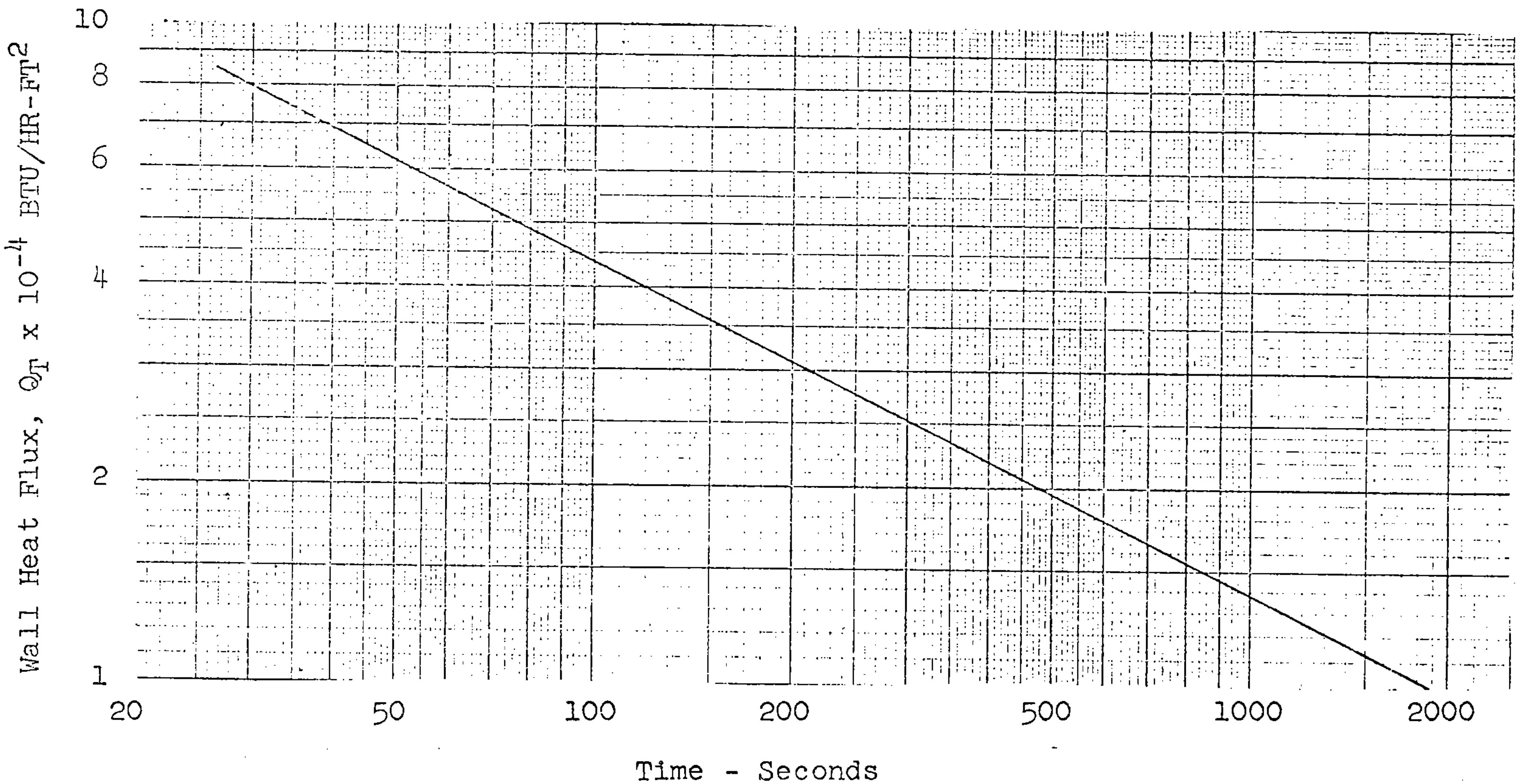


Figure VII- 3. Time Required to Raise Firebrick Wall Surface Temperature to 2000 $^{\circ}$F for Various Constant Heat Fluxes

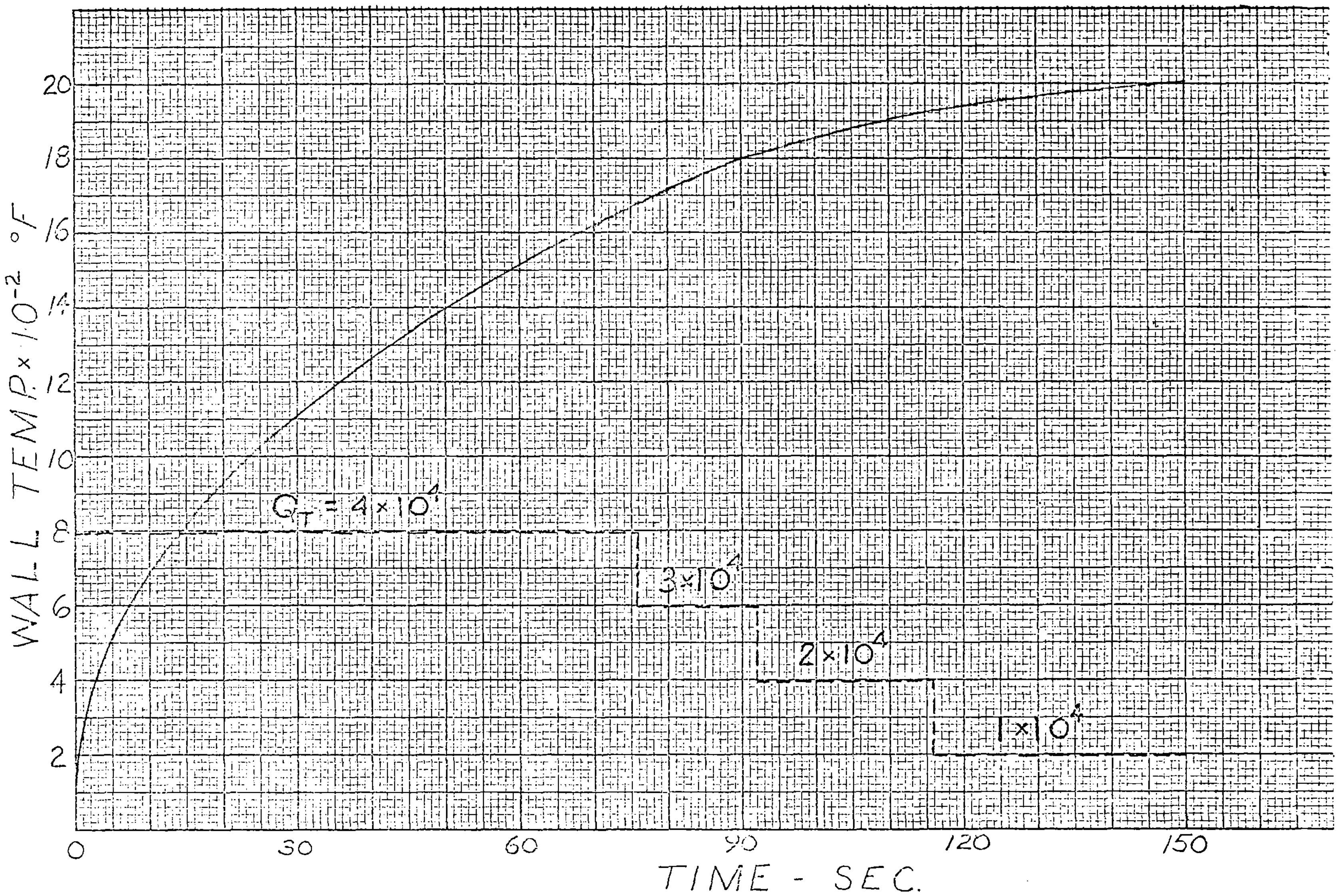


Figure VII-4. Estimated Transient Response of Firebrick Wall Surface Temperature

Figure VII-5. Estimated Transient Response of Steel Stand-Off Heated on One Side

VIII. FIELD FIRE SIMULATION CELL - CONCEPTUAL DESIGN

A. REQUIREMENTS

From the previously discussed thermo-chemical, topological, constructional and operational considerations the following criteria were evolved for the design of a facility whose objective is to permit simulation on a reproducible basis of a fire environment consistent with the Worst Credible Environment (WCE) encountered in a field fire following an aircraft crash.

1. Fire enclosure with walls providing required radiation background and provision for air supply. This is needed to assure proper irradiation of the manikin and to establish the required fire chemistry.

2. Size of fire enclosure to permit the manikin to receive no less than 95% of the total radiant heat generated in a field fire.

3. Fire enclosure wall protected in such a way as to prevent wind interaction with the fire as the manikin traverses the length of the fire, yet capable of permitting simulating flame plume motion in the same or in the opposite direction to the direction traveled by the manikin.

4. Fire basin capable of withstanding simulation of a dry ground field fire, with provisions for adjusting and maintaining various specified fuel pool heights.

5. Automated manikin carriage capable of variable speed adjustment to permit manikin fire exposure times between 3 and 30 seconds.

6. Overall facility designed for ease of operation and maintenance compatible with minimum construction cost and maximum operational safety.

B. <u>DESIGN CONSIDERATIONS</u> (See attached drawing CL101-1)

From earlier considerations average "steady state" flame temperatures of 2100°F are considered representative of field fires. To allow for uncertainties, a maximum of 2200°F is used for structural design criteria. Only those systems in direct contact with the fire are subject to this design temperature specification, namely the fire enclosure wall (referred previously as background heating wall), the building roof, the fuel pool basin and the manikin carrier respectively.

Because the exposure time for the manikin is assumed to be between three and thirty seconds, a twelve foot fire bed length was selected, which will permit traveling speeds for the manikin between 0.4 and 4 feet per second. Survivor speeds between these limits are considered realistic.

From previous wall heating calculations presented in Chapter VII, a minimum time of 150 seconds is required to bring the fire brick enclosure wall inner surface to "steady state" flame temperature. However, since the time period of interest for the fire is between three and thirty seconds it is obvious that wall preheating is required. Metal walls 1/16 inch thick can be expected to respond more rapidly; however the specified design temperature may affect the structural rigidity of such an assembly, adding constructional complexity which may ultimately negate the advantage accrued otherwise.

Electrical heating of the fire enclosure wall has been investigated and found to be unnecessarily complex and expensive.

A fire brick enclosure represents a compromise from the viewpoint of ease of operation, maintenance and initial Capital Cost. On the other hand, to satisfy the above design specifications, it is necessary to pre-heat the wall enclosure before the manikin is exposed to the fire. Preheating of the enclosure can be accomplished in two ways. By starting the fuel fire in the basin, heating the wall to the desired temperature and then proceeding to expose the manikin. Alternately, the wall can be heated independent of the fuel fire until the right temperature has been obtained. Then the fuel is introduced into the fire pit and ignited after which the manikin becomes exposed. The first operational sequence is simpler than the second one; however, there is associated with such an operation a time delay until the preheating has been completed, calling for a larger fuel storage capacity than for the other case. On the other hand, the use of a luminous wall may be preferred if preheating of the enclosure is to be achieved without resorting to a JP-4 fuel fire. Luminous walls make use of a premixed combustible mixture injected across a porous refractory wall. This mixture is ignited by a pilot flame located in the fire pit. Quick cooling of the enclosure can be achieved by shutting off the fuel in the mixture, letting only air flow through the porous wall. If need be, this flow of air can be replaced by a flow of inerting nitrogen. In addition, a porous wall enclosure on the fire will guarantee no oxygen starvation of the fire. Whether fire brick black-coated walls or non-coated porous refractory walls are used, provisions are made for independent valve regulated air injection into the fire pit.

To further guarantee proper irradiation of the manikin, a distance of 3 feet between each wall and the manikin is provided. When added to the approximately two-foot shoulder width of the manikin, this results in a fire cell width of eight feet as shown in the conceptual layout drawing.

To permit qualitative simulation of flame plume motion with respect to the direction traveled by the manikin, a system of ceramic fiber louvers has been suspended above the fire. Proper positioning of these louvers should allow directing the flame plume sidewise if needed, or directly upwards. When not testing, these louvers can be arranged to form a continuous roof over the cell enclosure. To prevent wind interaction with the flame engulfing the entering manikin, a second enclosure external to the fire enclosure is needed so that no external wind flow across the fuel is possible when the entering and exiting doors open to let the manikin in and out respectively. Enclosing the fire wall with another enclosure facilitates the design of a lateral plenum chamber which helps distribute incoming air to the inner enclosure. The top cover of this plenum chamber contains several adjustable air registers discharging into the atmosphere to permit by-passing the fire enclosure while at the same time providing convective cooling of the wall if necessary.

Air blowers located near the back wall are sized to handle air loads of up to 200 standard cubic feet per second. The discharge from each blower is split into two main headers, one of which feeds directly into the fire pit while the other feeds into a steel-lined enclosure which supports the porous refractory wall and helps encase the fuel pool basin. This flow of air permits cooling all metal structures in direct contact with the fire by forced convection. Heated air is finally discharged after traversing the length of the fire bed into the upper plenum chamber where it distributes evenly. The presence of this warm air in the plenum chamber insures a slightly positive pressure inside the facility which prevents external atmospheric air from entering the facility and mixing with the fire in an uncontrolled fashion, while at the same time providing sufficient air flow as required by the fire . In addition to air cooling, water cooling is indicated if preheating of the fire enclosure wall by using luminous walls is desired. In this case, substantial heating of the fuel pool basin is expected and cooling off by circulating water previous to pumping of the fuel into the basin is required to prevent ignition of the fuel before it reaches a specified liquid level.

The entrance and exit doors preventing the manikin from flame exposure before and after the test are located in such a way as to be part of the fire enclosure. These are quick-actuated sliding doors about two feet wide each, thus permitting a maximum opening of four feet. The sliding doors are supported from the fire brick wall, which is also part of the fire enclosure wall and ride on a track attached to the floor. The floor under the front sliding doors is a metal grill laid down on top of a concrete pit continuously purged with air. While the back sliding door is similar in design to the front, nitrogen purging has been provided to prevent the manikin from continuing to burn after leaving the fire area.

For safety reasons, proper air ventilation is highly desirable when testing is concluded, to guarantee the elimination of combustible mixtures inside the facility. The elimination of pockets where combustible mixtures may become trapped is of paramount importance in the final selection of the structure. After careful considerations, an open roof type facility was selected. However, because of weather protection considerations, a rolling cell shed with corrugated roof and side walls has been chosen as the most practical cover for the FFSC.

In the event of an emergency requiring a quick fire shutdown, fuel flow is discontinued and a valve connecting the fuel fill line to the emergency withdrawal tank opened. Because this tank is under vacuum, the flow of fuel is reversed thus permitting quick draining of the fuel pool. As soon as the fuel drainage has been completed, flow of nitrogen is initiated into the fuel fill line connecting to the fuel basin, for the purpose of quenching and extinguishing the fuel fire.

C. PROPOSED FACILITY OPERATION

A full operational sequence cannot be established at this time, since no information is available on the number of manikins to be tested, nor their instrumentation philosophy. However, some operational sequence has been assumed during the facility conceptual design phase, consistent with ease of operation and maximum safety of the personnel involved in the operation and maintenance of this facility.

The criterion of operation adopted here is one which permits pre-heating of the fire enclosure wall directly by the JP-4 fire. This undoubtedly represents the simplest mode of operation. After proceeding to roll away the facility shed, filling up of the fuel basin is initiated until a specified liquid level is obtained. Simultaneously, the flow of air is started both across the fire enclosure as well as into the plenum chambers. The air registers above the plenum chambers are then fully opened to permit thorough purging of the plenum chamber enclosure. Concurrently, the exhaust louver system is positioned to give the desired fire plume motion, while the sliding doors are cycled open and closed repeatedly.

The fully instrumented manikin is then mounted securely to the carrier, while both front and back concrete pits are being fully air purged. It is very important that the main facility door be securely closed after the sliding doors are set closed. The emergency withdrawal tanks are isolated through isolation valves from the fuel fill line and the mechanical vacuum pumps turned on until evacuation of the emergency tanks below 1 micron of mercury is obtained at which time the vacuum pumps are isolated from their respective tanks. Just prior to ignition of the fuel pool, the water pumps are activated by opening the complete re-circulation system, making sure the flow of coolant is on. Air registers on top of the plenum chambers are re-adjusted to close position while the back concrete pit is transferred from air purge to a nitrogen purge mode. Ignition of the fire is to be accomplished by triggering an electrical igniter or its equivalent. Temperature instrumentation for both the fire enclosure wall and the fire itself is monitored until close agreement between them is obtained, at which time the sliding front door and the manikin carrier are activated. The back sliding door is finally activated using a delay switch sequentially coupled to the front door. Upon completion of the manikin run, the rear external facility door will be opened to permit removal of the manikin after complete quenching by nitrogen has been completed.

In the event that an emergency arises where it becomes desirable to terminate the fire, isolating valves to the emergency withdrawal tank are to be opened fully to permit withdrawal of the remaining fuel in the fuel basin, followed by the activation of the emergency nitrogen system which will then flood the fuel basin until the fire becomes extinguished.

IX. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

After carefully analyzing the dominant effects present in a real field fire to determine whether or not they can be simulated in an FFSC, the following conclusions have been reached:

1. Analytical modeling of the important characteristics of a JP-4 field fire is possible. A reasonable agreement between the Worst Credible Environment in a real field fire following an aircraft crash and the WCE of an FFSC has been obtained. Air entrainment rates into the fire derived from the obtained analytical model were used as an input to the conceptual design of an FFSC.

2. Engineering feasibility on the basis of JP-4 fuel results from the analytical model was successfully established. A conceptual design layout (Enertech Inc. Drawing CL-101-1) has evolved from the engineering feasibility studies of a facility which is unique in its characteristics, yet operationally flexible, easy to operate and maintain, and possesses a maximum degree of intrinsic safety. The fact that JP-4 fuel was used as a design fuel does not restrict the use of this facility. However, if burning of fuels other than JP-4 is desired, different air entrainment rates may be required for the proper "tuning" of the fire.

3. A preliminary estimate based on the proposed field fire facility conceptual design layout indicates a cost range between $50K and $75K, depending on the operational sequence of the facility. For a more definite estimate detailed engineering drawings and specifications are required.

B. RECOMMENDATIONS

On the basis of conclusions generated by the results of this study in which thermo-chemical, hydrodynamic and engineering feasibility of simulating a field fire was considered, it is recommended that a facility using the proposed conceptual layout

(Enertech Inc. Drawing CL-101-1) be built and operated for the purpose of simulating a field fire environment following an aircraft crash. The proper implementation of this recommendation involves the following steps:

a. Preparation of engineering specifications for purposes of securing potential contractor bids.

b. Preparation of a test program, reflecting the philosophy of operation desirable from the viewpoint of frequency of testing and the number of manikins and/or other use of the facility for biological fire injury studies. The final objective of this recommendation is to permit development of a facility operational sequence which perhaps may impose other more severe storage and maintenance needs than previously considered and which ultimately will have to be reflected in the final engineering design.

c. Establishment of engineering manikin instrumentation criteria to properly ascertain interface relationships with the FFSC.

d. Investigate extension of the use of the facility for fuels other than JP-4. This requires knowledge of air entrainment rates which can be obtained by use of the analytical model developed in this report applied to different fuels.

e. That procurement be broken down into sequential steps a , b and c respectively, before proceeding with the recommendation.

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GENERALIZED VIEW SHOWING ORIENTATION OF SECTIONAL VIEWS

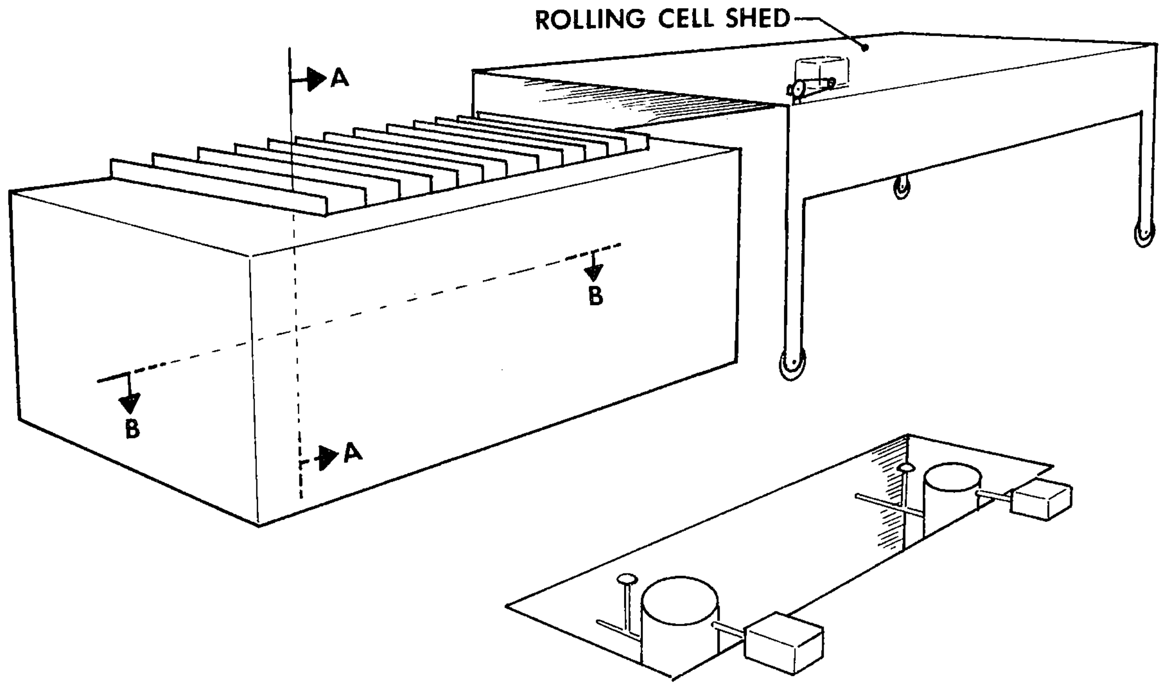
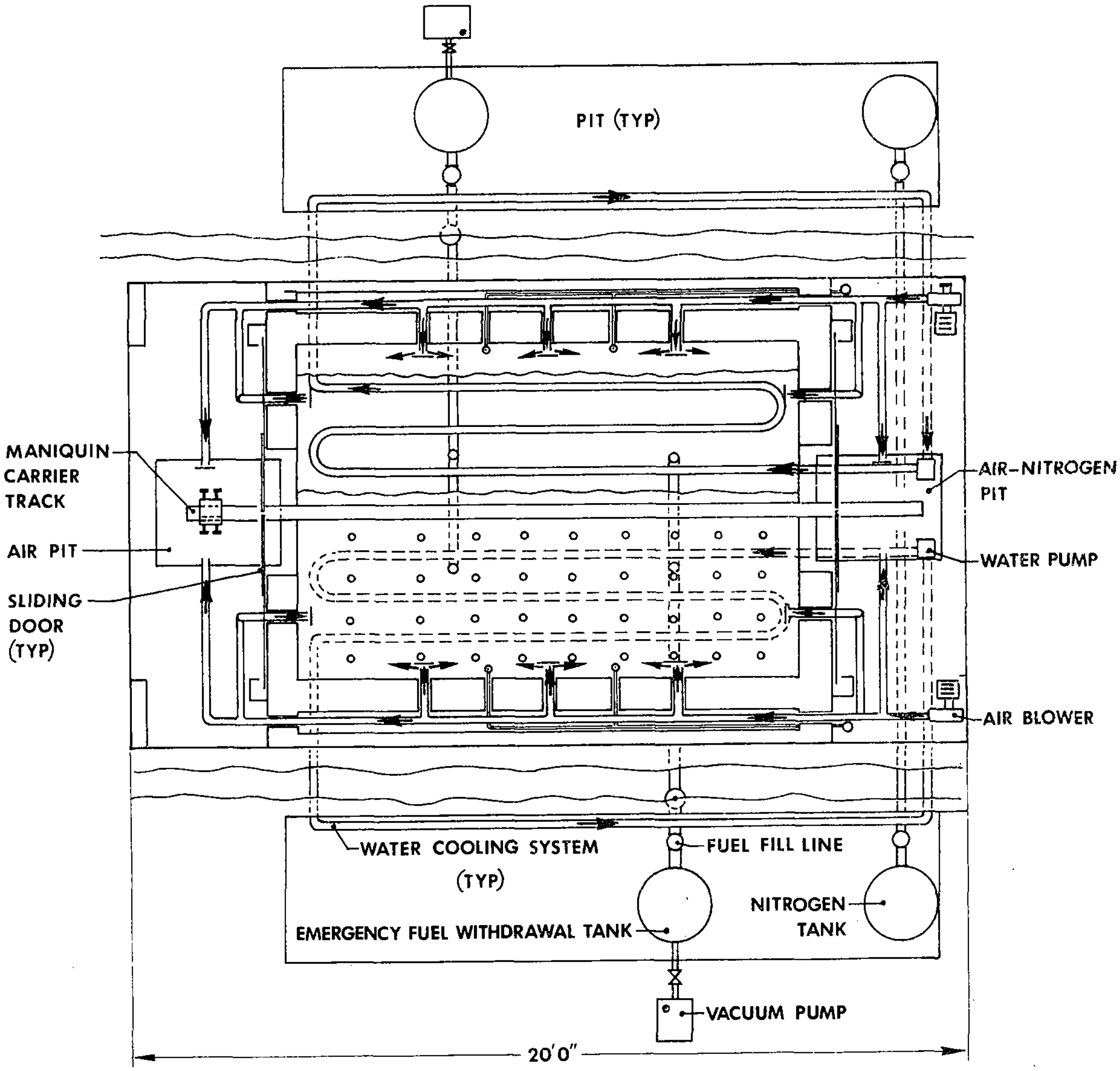


FIGURE A

FIELD FIRE SIMULATION CELL

ADAPTED FROM ENERTECH DRAWING CL 101-1

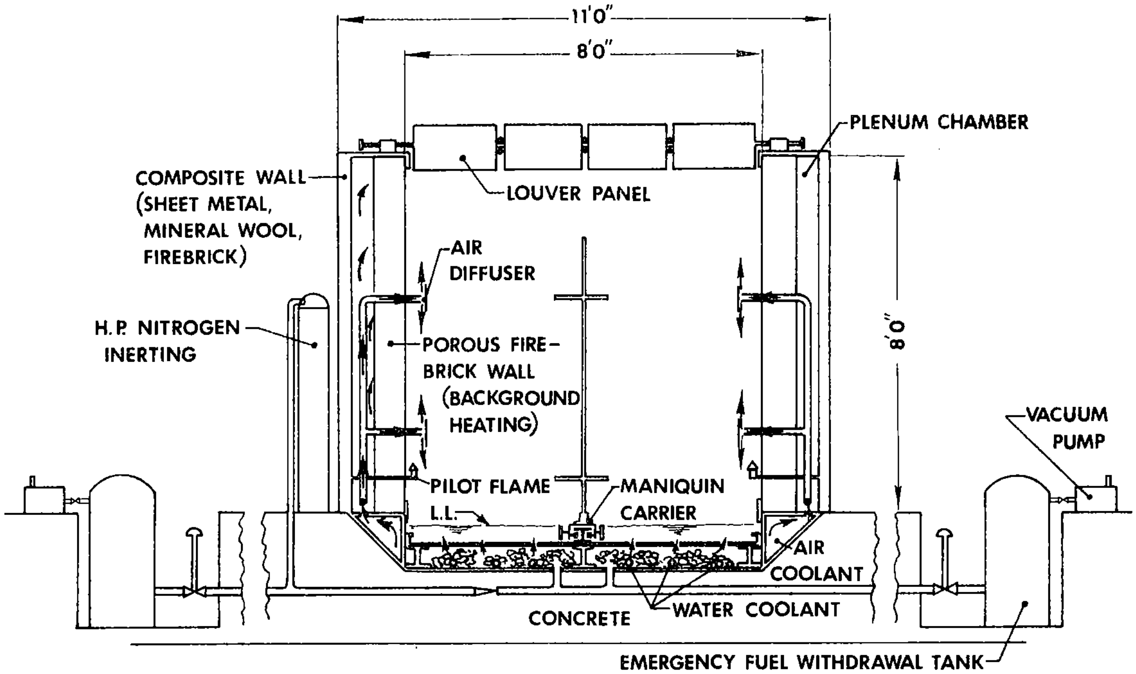


SECTION B-B

FIGURE B

HORIZONTAL CROSS SECTION OF FIELD FIRE SIMULATION CELL

ADAPTED FROM ENERTECH DRAWING CL 101-1



SECTION A–A

FIGURE C

VERTICAL CROSS SECTION OF FIELD FIRE SIMULATION CELL

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13. ABSTRACT

This report sets forth the conceptual design for a facility intended for development and evaluation of thermal protective clothing in a reproducible fuel fire environment. The methods developed relate thermal characteristics of fabrics to biomedical aspects of burn prevention. A number of bioengineering problems are identified, the resolution of which is expensive and time consuming. It is concluded that construction of the facility designed is technically feasible. Due to the magnitude and complexity of the bioengineering problems identified, and because of advances in laboratory testing methods, however, construction of such a facility is not considered to be a prudent expenditure of public funds at this time. Operationally oriented bioengineering/aeromedical evaluation of thermal protective clothing systems remains essential.

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